ANNUAL REPORT

1984

U. S. WATER CONSERVATION LABORATORY
U. S. Department of Agriculture
Agricultural Research Service
Western Region
4331 East Broadway Road
Phoenix, Arizona 85040

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PERSONNEL

The laboratory staff is as follows:

Permanent Employees:

Aagard, Rita L.	Clerk-typist (resigned 2/84)
Allen, William J.	Agricultural Research Technician (Plants)
Allen, Stephen	Plant Physiologist
Auer, Gladys C.	Physical Science Technician
Barrett, Paul J.	Physical Science Technician
Bell, Frieda L.	Secretary
Bouwer, Herman	Research Hydraulic Engineer, Research Leader, and Laboratory Director
Bowman, Robert S.	Soil Scientist
Bucks, Dale A.	Agricultural Engineer
Clawson, Kirk L.	Soil Scientist
Clemmens, Albert J.	Research Hydraulic Engineer
Davis, Sonya G.	Engineering Draftsman
Dedrick, Allen R.	Agricultural Engineer
Ehrler, William L.	Plant Physiologist (resigned 1/84)
Ezra, C. Elaine	Physical Scientist (resigned 3/84)
Fink, Dwayne H.	Soil Scientist
French, O. Fred	Agricultural Research Technician
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Clerk-typist
Hunsaker, Douglas J.	Agricultural Engineer
Hunter, Koelle	Secretary (resigned 10/84)
Idso, Sherwood B.	Research Physicist
Jackson, Ray D.	Research Physicist
Jaynes, Dan B.	Soil Scientist
Kapfer, Raymond E.	Engineering Technician
Kelly, Harold L. Jr.	Biological Technician
Kimball, Bruce A.	Soil Scientist
Legard, Wilde W.	Agricultural Research Technician
Lewis, Clarence	Machinist
Martinez, Juan M. R.	Hydrological Technician
Mastin, Harold L.	Computer Assistant
Miller, J. Bennett	Biological Laboratory Technician
Mills, Terry A.	Computer Specialist
Mitchell, Stanley T.	Physical Science Technician
Moran, M. Susan	Physical Scientist
Murphy, B. Lenore	Secretary
Nakayama, Francis S.	Research Chemist and Research Leader
Padilla, John	Engineering Technician
Pettit, Dean E.	Electronic Engineer
Pinter, Paul J. Jr.	Research Biologist
Rasnick, Barbara A.	Physical Science Technician
Reginato, Robert J.	Soil Scientist and Research Leader
Replogle, John A.	Research Hydraulic Engineer & Research Leader
Rice, Robert C.	Agricultural Engineer
Rish, Shirley A.	Secretary

Personnel (continued)

Schnell, Stephanie A.	Biological Technician
Seay, L. Susan	Clerk-Typist
Seay, Ronald S.	Agricultural Research Technician
Thompson, Anson E.	Research Plant Geneticist

<u>Temporary Employees</u>:

Anderson, Mike	Co-Op Agreement (Biological Technician)
Carney, Brian	Computer Clerk
Dierig, David A.	Agricultural Research Technician
Gorhing, Tom	Engineering Technician
Jacobs, John S.	Electronic Technician
Karpinski, Sandra M.	Work Study (Biological Aide)
Kraft, John	Physical Science Technician
Lendriet, Michelle	Biological Aide
Moss, Scott	Biological Aide
Pendrick, Annette M.	Biological Aide
Prescott, Jack	Physical Science Aide
Reinink, Yvonne	Research Assistant (ASU)

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TITLE: CUPHEA GERMPLASM EVALUATION, DEVELOPMENT, AND DOMESTICATION

NRP: 20160 CRIS WORK UNIT: 5090-20163-003

INTRODUCTION:

Species of Cuphea have potential for domestication and development as a new crop for the production of lauric and other medium-chain fatty acids. The U. S. is dependent upon imports of coconut and palm kernel oils for its total supply essential to the manufacture of soaps, detergents, lubricants, and other related products. Initial field trials in Oregon in 1983 indicated that Cuphea has good prospects for agronomic adaptation. However, the plant needs to be improved to fit current farm production technology. Slow emergence and seedling growth, seed dormancy, indeterminate plant growth and flowering, sticky plant hairs, and excessive seed shattering are some of the major constraints to domestication.

PROCEDURE:

The USDA/ARS, through a Specific Cooperative Agreement (SCA No. 58-9AHZ-3-744) with the Oregon State Agricultural Experiment Station, provides funding for research to develop Cuphea as a new crop for production in Oregon and the Pacific Northwest. This is a unique, equally-funded, 3-way effort of USDA/ARS, Oregon State AES, and member companies of the Soap and Detergent Association. Research funded under this SCA is conducted under CRIS No. 5090-20163-003A, which is keyed to the inhouse CWU 5422-20160-004 at the USWCL in Phoenix, AZ. Dr. Anson E. Thompson serves as the ADODR on this SCA, and provides coordination and liaison within ARS and with state agricultural experiment stations and industry for all aspects of Cuphea research.

A total of 8 projects are funded by and contribute to the research program in Oregon. Project titles and investigators are as follows:

1. Plant Breeding - Dr. Frank Hirsinger (resigned in December, 1984)
2. Agronomy - Dr. Gary D. Jolliff
3. Weed Control - Dr. Arnold P. Appleby
4. Soil Fertility - Dr. E. Hugh Gardner
5. Seed Dormancy & Technology - Dr. Donald F. Grabe
6. Mechanical Harvesting - Prof. Dean E. Booster
7. Biochemistry/Fat Biosynthesis - Dr. Ian J. Tinsley
8. Climatic Adaptation - Prof. P. Vance Pumphrey, Prof. Charles E. Stanger, and Prof. John A. Yunger

RESULTS AND DISCUSSION:

Initial USDA/ARS funding to this program for the amount of $25,000 was made in 1983. This amount was matched by the Proctor and Gamble Company with the Oregon State Agricultural Experiment Station providing equal support. Research on this program in 1983 was confined chiefly to

aspects of plant breeding and weed control. Finalization of the total 3-way funding package was delayed until well into the 1984 growing season. However, most of the planned experiments were initiated in a timely fashion. Performance of these experiments, which were approximately 4 acres in size, was observed by around 50 scientists and industry representatives at a field day and conference at Corvallis, OR, on August 28-30. Detailed reports of the experiments are on file and available on request.

A plant breeding nursery was established in Corvallis containing populations of Cuphea wrightii, C. laminuligera, C. leptopoda, C. lutea, and the C. wrightii x C. tolucana hybrid. Small populations of the nonsticky mutants of C. lanceolata, C. procumbens, and C. tolucana were also planted. A total of 96 progeny of single plant selections from 5 species were evaluated and comparative ratings were made on emergence, stand establishment, flowering, and seed set (Table 1). Growth and development during the season were adequate. However, early, persistent rains occurred in September before seed maturity, resulting in severe seed shattering and a major reduction in yield. In most instances, the recovery of seed was significantly less than that utilized for planting. In general, the comparative performance of C. wrightii was lower than had been observed at Davis, California in 1982 and 1983 and at Corvallis in 1983. The performance of C. lutea and C. laminuligera appears promising.

A hybrid breeding program of the cross-pollinating species--C. laminuligera, C. lanceolata, C. leptopoda, and C. procumbens was initiated by establishing 40 isolated plots containing one plant of each species. Due to the limited irrigation facilities in some locations, the number from which seeds could be harvested was follows: C. lanceolata (5), C. procumbens (17), C. laminuligera (20), and C. leptopoda (23). It is recommended that the program be continued only with C. laminuligera and C. leptopoda for at least 3 more generations. The resulting inbred lines can then be tested for combining ability by top crossing. The other 2 species should be screened for at least one generation without isolation for detection and selection of possible interspecific hybrids that may have occurred.

In general, the early fall rains severely hampered the various agronomic experiments since seed yields could not be taken. However, the herbicide screening test provides some leads that may permit the development of preliminary recommendations for weed control. Cuphea wrightii appeared to give a good growth response to applications of nitrogen, but the effects on seed yield could not be determined. Field research studies were initiated on factors influencing seed development, maturation, dormancy, and the quantification of seed production. The early rains also hampered these studies and limited the quantity of seed that was to be utilized for further evaluation in the laboratory.

Dr. Hirsinger coordinated a trial to evaluate the performance of C. wrightii at 9 locations: Corvallis, Hermiston, Ontario, and Medford, OR;

Ames, IA; West Lafayette, IN; Jacksonville, IL; Phoenix, AZ; and Göttingen, W. Germany. Results were variable, and yield data were not obtained at several locations for a variety of reasons (Table 2). In general, earliest emergence and flowering were observed in the Midwest, and good seed yield and quality were obtained at Jacksonville, IL. The highest seed yield was obtained at Medford in southern Oregon. Good plant growth and potentially good seed production were also observed in eastern Oregon. In Arizona, because of heat stress, only a few seeds were produced.

SUMMARY AND CONCLUSIONS:

The early fall rains experienced this year in the Willamette Valley may preclude this location as a primary production area for Cuphea. More attention should be given to evaluating areas in southern and eastern Oregon. Although the results of the Cuphea Regional Trial were variable for the first year, the information obtained is useful, and the trial should be continued and expanded if possible. A uniform format needs to be developed so that more valid comparisons can be made among results obtained at different locations.

The two species--*C. lutea* and *C. laminuligera*--appeared to have as good or perhaps better potential than *C. wrightii* for production in this area. However, the quantity of seed available is limited (*C. lutea* ± 3 lbs., *C. laminuligera* ± 7 lbs.), and must be increased before wide-scale testing can be attempted. Approximately 260 lbs. of *C. wrightii* seed are currently available as remnants of the 1983 harvests. There is a serious need to evaluate a wider array of accessions from these species. Most of the seed at Corvallis originated from a very limited number of accessions tracing back to germplasm collections made in wild habitats in Mexico. Attention should be given to additional germplasm collections in Mexico as well as Brazil and other South American locations.

Adequate funding is currently being allocated to the cooperative research program at Oregon State University by both USDA/ARS and industry. If new funds are available from either USDA/ARS or industry, such funds should be allocated to other locations to support basic research and germplasm enhancement, and for germplasm evaluation and testing in other potential areas of adaptation and production.

Dr. Frank Hirsinger, who played a lead role in the area of plant breeding and germplasm evaluation on this program, resigned and left the program at the end of the year to accept a position with Henkel KGaA in Düsseldorf, W. Germany. Oregon State University is actively recruiting a tenure-track academic position in the area of plant breeding and genetics to fill this key area. It now appears unlikely that this position will be filled before the spring planting season. Plans must be made to plant populations of the major Cuphea species in locations at southern and eastern Oregon in addition to Corvallis to provide the new scientist material to evaluate during the 1985 growing season. Dr. Thompson will provide assistance to the new scientist as needed during the 1985 cropping and harvesting season.

Since most of the program started late and the heavy fall rains disrupted much of the planned research, plans for most of the 1985 field experiments will be essentially the same as those outlined for 1984. However, more attention should be given to evaluation of plantings in southern and eastern Oregon. Plans are being made to continue to cooperatively evaluate *C. wrightii* at various locations throughout the country. Plans are being made to increase seed of several species, with special emphasis on *C. lutea* and *C. laminuligera*.

Positive steps have been taken to provide better administrative coordination and management of the program. Dr. Wilson Foote, who retired recently as Associate Director of the Oregon State Agricultural Experiment Station, has assumed the role as Cuphea Research Coordinator on a part-time basis, starting January 1, 1985.

REFERENCES:

None

PERSONNEL: A.E. Thompson, ADODR; G.D. Jolliff, Principal Investigator, and F. Hirsinger (Oregon State University, cooperators).

TABLE 1. PERFORMANCE OF PROGENY OF SINGLE PLANT SELECTIONS OF CUPHEA SPECIES. OREGON STATE UNIVERSITY, CORVALLIS, OREGON - 1984 (PLANTED 5/15/84).

		Comparative ratings * (mean + S.E.)			
Species	Number of selections	Emergence 6/13	Stand establishment 7 16	Flowering 7/30	Seed set 9/17
C. wrightii	22	3.2 ± 1.1	3.7 ± 0.9	2.4 ± 0.6	3.2 ± 0.8
C. wrightii x C. tolucana	10	2.0 ± 0.7	1.9 ± 1.0	2.0 ± 0.7	2.6 ± 0.7
C. laminuligera	23	3.1 ± 0.9	3.8 ± 1.0	3.9 ± 0.9	4.6 ± 0.8
C. leptopoda	37	2.0 ± 1.3	2.2 ± 1.3	1.0 ± 0.8	1.2 ± 1.0
C. lutea	4	4.7 ± 0.5	4.7 ± 0.5	4.0 ± 0.0	5.2 ± 0.5

*1 = lowest, 6 = highest expression of observation

Table 2. Cuphea regional experiment 1984: Data from different experiment stations

Column		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Emergence				Leaf stage			Branch-ing	Flowering		Ripening			Seed information			
Station	Pltg. date	Begin		1st	2nd	2-lf	6-lf	1st ht.		time	2nd ht.	time	3rd ht.	4th ht.	total harv.	yield/ row-m	no.of harv.	quality[6/]
		days*	no.	no.	no.	days*	days*	cm	days*	days*	cm	days*	cm	cm	g	g/m		%
Corvallis, OR	5/15	-	-	-	320	31	48	6	59	73	23	97	28	34	881	ca. 10	1	40[7]
Hermiston, OR	4/20	17	-	-	400	-	-	-	-	94	-	-	-	38	0[3]	-	-	-
Ontario, OR	4/18	-	7	19	43	48	64	7	76	96	14-15	120	20	27	ca.5[4/]	ca.0.3[4/]		20
Medford, OR	-	-	-	-	-	-	-	-	-	-	-	-	-	-	988	ca.27	2	-
Ames, IA	6/1	6	6	96	95	17	26	6	48	40	12	53	18	23	50	1.4	2	40
W.Lafayette, IN	6/20	6	4	30	31	19	23	5	26	34	10	61	-	30	-[5/]	-	-	-
Jacksonville, IL	5/23	7	(50%)	-	-	14	18	-	-	49	43	96	-	56	857	ca.10	2	80
Göttingen, FRG[1/,2/]	5/16	-	-	-	-	-	-	-	-	76	-	124	-	-	-	-	-	-
Phoenix, AZ	4/20	11	15	46	53	31	39	2	46	56	8	72[8/]	22	-	-	-	0	-

* Days after planting
1/ Data not yet available
2/ According to letter information
3/ Seeds could not be harvested due to weekly wind storms and light rains
4/ Seeds not cleaned
5/ Not harvested due to immature seeds
6/ In % of mature seeds
7/ After several seed losses due to rain from the beginning of Sept. to end of season. Immature seeds were harvested on Oct. 3.
8/ Only few seeds produced due to heat stress

TITLE: GERMPLASM DEVELOPMENT AND DOMESTICATION OF CUPHEA AND OTHER CROP SPECIES

NRP: 20160 CRIS WORK UNIT: 5422-20160-004

INTRODUCTION:

Numerous studies have identified the need for, and potential of new crops research and development. Development of new crops would provide the basis for enhancing economic development, diversifying agricultural production, reducing reliance upon imports, providing new commodities for export, improving the balance of payments, developing a strategic reserve of certain commodities necessary for national defense, providing a more varied diet, and improving feeds for animals. High yields of traditional crops in the arid Southwest depend upon extensive irrigation. New crops with low water use will be needed if agriculture is to persist in the region.

The U.S. chemical industry is heavily dependent upon imported coconut and palm kernel oils as the primary source of lauric acid for manufacturing soaps, detergents, lubricants, and other related products. Seed oils from species of *Cuphea* contain high levels of lauric and other medium-chain fatty acids. Seed dormancy, seed shattering, sticky glandular hairs, and indeterminate patterns of growth and flowering are major constraints to domestication.

The U. S. is completely dependent upon imported castor oil for its total supply of hydroxylated fatty acid. Castor oil is a strategic material of industrial importance as chemical feedstocks for the production of lubricants, plasticizers, protective coatings, surfactants, and pharmaceuticals. Production of castor beans in the U.S. is inhibited by the high levels of allergenic reactions associated with its production and high levels of toxicity in the seeds. Seed oils from species of *Lesquerella*, many of which are adapted to arid lands, contain sizable quantities of three hydroxy fatty acids. Domestication of adapted species of *Lesquerella* and development of a new domestic crop to replace castor appears feasible.

Research on domestication of wild plant species such as *Cuphea* and *Lesquerella*, the evaluation and development of germplasm leading to useful varieties, and concurrent development of appropriate crop production practices are long-term, high-risk research activities. Exact timetables are difficult to construct, and 10 years is a conservative estimate for attaining minimal objectives.

PROCEDURE:

This project has responsibility for the following essential activities relative to the development of germplasm and domestication of new crop species. Primary emphasis is on species of *Cuphea*, and secondary emphasis on species of *Lesquerella*:

- Assembling, multiplying, and maintaining working germplasm collections. Distributing available seed stocks to bonafide requesters.

- Evaluation of germplasm with special emphasis on potential adaptation to semiarid and arid conditions. Identification and selection of agronomically promising species and accessions.

- Germplasm enhancement. Employment of conventional breeding and genetic techniques to develop useful germplasm and breeding lines. Employment of both intra-and interspecific crossing to obtain new genetic recombinations to remove constraints to domestication and productivity. Improved germplasm will be made available to cooperative research and developmental programs for evaluation and utilization.

- Liaison and coordination of national Cuphea research program.

  - Provide coordination within USDA/ARS.

  - Provide liaison and coordination with universities and state agricultural experiment stations.

    - Oregon State University - Specific Cooperative Agreement (No. 58-9AHZ-3-744). Development of total production system including germplasm evaluation, breeding and genetics, and development of appropriate cultural and harvesting systems. Primary emphasis on annuals adapted to Northwest climatic conditions. A unique 3-way, equally-funded program involving USDA/ARS, Oregon SAES, and member companies of the Soap and Detergent Association.

    - University of Arizona - Broadform Cooperative Agreement (No. 58-9AHZ-3-38). Cooperative research on interspecific hybridization and cytogenetics of Cuphea.

    - Purdue University - Broadform Cooperative Agreement (No. 12-14-3001-259). Cooperative research on development of Cuphea tissue culture methodology.

  - Provide liaison with industry. Participate in planning, development and evaluation of Cuphea research program with Technical Subcommittee-Cuphea Plant Research Committee of the Glycerine and Oleochemical Division of the Soap and Detergent Association.

RESULTS AND DISCUSSION:

Assembling, Multiplying, Maintaining, and Distributing Working Germplasm Collections:

Cuphea

A working germplasm collection of Cuphea has been assembled and currently contains 274 accessions of 59 of the 252 known species from 9 of the 13 sections of the genus. In many instances, numbers of seeds received were very limited and some were of doubtful viability. Attempts were made to germinate seed of 250 of the accessions to obtain plants for evaluation and seed increase. A total of 120 accessions were

successfully germinated. However, 130 did not germinate even though attempts were made to facilitate germination by excision of embryos from the seeds. A total of 92 accessions and 13 species were lost due to failure of germination and lack of remnant seed. Results of this activity and current status of the USDA/ARS Cuphea Working Germplasm Collection are summarized in Table 1.

Lesquerella

The USDA/ARS Lesquerella working germplasm collection consisting of 93 accessions of 23 species has been assembled. Approximately one-third of these species are native to the Southwest (Table 2). Seed viability and germination percentage varied considerably although some germination was obtained from over 92% of the accessions received. Most of the seed had been collected in 1966-1972, and seed dormancy per se was not a problem.

Evaluation of Germplasm:

Cuphea

A field experiment was designed to determine water usage of 5 Cuphea species under 3 rates of irrigation (wet, medium and dry) based upon soil water depletion monitored by a neutron moisture meter. The 5 species were *C. wrightii*, *C. tolucana*, a putative amphidiploid hybrid of *C. wrightii* x *C. tolucana*, *C. laminuligera*, and *C. procumbens*. The experiment was conducted at the University of Arizona Maricopa Agricultural Center on a sandy loam soil. The experiment was replicated 4 times with the 3 rates of water application making up the main plots, which contained 6 subplots of the 5 species (*C. wrightii* was planted in duplicate). Each main plot consisted of 8-40 inch beds with 6 containing the tested species plus 2 beds serving as guards. Border dikes separated each main plot in order to effectively apply and contain the 3 irrigation treatments. Each subplot consisted of 3-20 foot long beds that contained 2 rows of plants/bed with a 10 inch interrow spacing. Such spacing provided a planting density of approximately 31,000 plants/acre (78,000 plants/hectare). Approximately 14,000 plants were transplanted into the field on April 12-13, 1984. Transplants were sprinkler irrigated until established. By June 1st, gated pipes were installed to deliver the 3 application rates by furrow irrigation.

By June 1st, only 2 species *C. procumbens* and the *C. wrightii* x *C. tolucana* hybrid exhibited adequate survival rates of 80-90%. Survival counts for *C. wrightii*, *C. tolucana*, and *C. laminulgera* were less than 10%. Factors contributing to the loss of stand were high temperatures and poor water quality from a well with a high salt content that was inadvertently used for the first establishment application. Another important factor was the maturity and condition of the plants at transplanting. A delay in field preparation resulted in a delay in planting, and many of the transplants were flowering and some were even beginning to set seed. The advanced maturity of these plants interacting with the environmental factors apparently inhibited development of new vegetative growth necessary for successful plant establishment.

The irrigation study was still carried out with the 2 surviving species. Irrigation was scheduled at 50% soil moisture depletion for the wet treatment, 65% for the medium treatment, and 80% for the dry treatment. These percentages were calculated by using the 0 to 50 cm depth of soil. Two neutron access tubes were installed in each main plot to determine water depletion. Even at these low depletion rates, plant loss continued throughout the summer months in the dry treatment.

Approximately 20 inches of water was used to establish these plants from the planting date in mid April until June 1st. From June 1st until mid August the wet treatment received 27 inches of water. The medium treatment received 18 inches, and the dry treatment received a total of 14 inches for the 75 day period. The only apparent difference in amount of water used between these 2 species was in the "dry" treatments. More plants of C. procumbens were lost throughout the season than for the amphidiploid hybrid in this treatment, thus indicating that C. procumbens has a higher water requirement.

Throughout the experiment both species flowered. The flowers of C. procumbens appeared normal, but those of the hybrid did not develop normally. Many of the flowers failed to develop petals. Very little seed set was observed on either species in any of the water treatments. Seed abortion was attributed to the high temperatures experienced throughout the growing season. The experiment was abandoned in September with no yields taken, and total water requirements for production of Cuphea was not determined.

A total of 569 plants of 50 germplasm accession of 15 species were also transplanted to the field at Maricopa on April 19th. By the middle of August, plants of 48 accessions had died, leaving only 161 plants of 2 accessions of a perennial species C. angustifolia. This species flowered and produced a small amount of seed later in the fall after temperatures had decreased. A total of 374 plants of 71 accessions of 15 annual species were transplanted in April into plots at the U. S. Water Conservation Laboratory (USWCL) in Phoenix. Only about 20% of the plants and accessions survived the summer. In contrast, 303 plants of 36 accessions of 16 perennial species were transplanted in plots at the USWCL, and only 1 accession was lost. Approximately 77% of the perennial plants survived the season, and many produced seed in the fall.

Foilage of all Cuphea species appears to be susceptible to light frosts although some differences in degree of sensitivity have been observed. Two accessions each of the perennials C. angustifolia and C. llavea survived the winter of 1983-84 in outdoor plantings at the USWCL, and regrew vigorously in the spring from plant crowns, underground stems and roots. Plants of 31 accessions of 11 perennial species are planted in outdoor plots at the USWCL to observe their capacity to over winter and survive.

Adaptation of C. wrightii was evaluated in the Imperial Valley at the USDA/ARS Desert Irrigation Center at Brawley, California. Approximately 3,500 seedling plants were transplanted by machine on May 8th as single

rows on 8-500 foot long, 40 inch beds. The soil was a relatively heavy clay loam. Spacing between plants within rows was 14 inches, giving a planting density of approximately 11,200 plants/acre (28,000 plants/ hectare). One half of the plants were grown in speedling trays at Brawley and were approximately 2 weeks advanced in maturity compared to the balance of the plants grown at the USWCL in Phoenix. The latter were seeded on April 13 and seedling plants pricked off into speedling trays on April 20th. At the time of planting, the Phoenix plants were transported to Brawley. These plants were in very good condition, well rooted, from 2 to 3 inches in height, in the 6th leaf stage, and starting to branch. The Brawley grown plants were from 4 to 5 inches in height and well branched and rooted at the time of transplanting. Sprinkler irrigation was used for establishment and water application was later shifted to furrow irrigation. It was originally intended that 3 levels of irrigation would be imposed and water usage and rate of soil water depletion monitored by a neutron moisture meter.

Loss in plant stand at Brawley commenced early and continued as the season progressed. Since loss in stand was so rapid, a decision was made to forego establishment of differential irrigation treatments. In mid-June, 45 days after transplanting, the stand was estimated to be only approximately 30%. The largest plants were only approximately 6 to 8 inches in height and flowering. However, most of the flowers showed signs of heat stress, were abnormal in appearance, and failed to develop normal petals. Very little seed set was observed. Some plants were dwarfed and yellowing. High salinity may have been a contributing factor since obvious salt deposits were observed on top of the beds. Continued stand depletion and poor plant growth forced the termination of the experiment in mid-July. A few plants produced a very small amount of seed at this time, but no yield data were taken.

Cuphea wrightii was direct-seeded in replicated plots at the Maricopa Agricultural Center on April 20th as part of the Cuphea Regional Experiment managed by Dr. Frank Hirsinger at Oregon State University. In addition to rows seeded with a Planet Jr. drill, plantings were also made by fluid drilling. An additional planting was made on May 2nd since plant stands in the fluid drilled plots were very low. Data were taken periodically on stand counts, branching, plant height, flowering and seed set. Plant growth and flowering were minimally adequate, but seed set was very limited, most probably due to high seasonal temperatures. As with the other plantings, flower development was somewhat abnormal, most probably due to heat stress. No attempt was made to obtain yield data or harvest the limited amount of seed produced. Data on emergence, plant growth and stands are summarized in Table 3.

A replicated, date of planting experiment was designed to determine the feasibility of producing Cuphea as a direct-seeded fall crop in central Arizona. Seed of *C. wrightii* was planted at 10-day intervals with a Planet Jr. drill, starting August 27th. Good germination and stands were obtained for the first 2 plantings. A soil-borne pathogen severely reduced stands in the last 2 plantings. Some plant losses were also observed in the first 2 plantings. Infected plants and soil were taken to the Department of Plant Pathology of the University of Arizona at

Tucson for possible identification of the causal organism. Flowering occurred 43, 41, 40, and 44 days after planting, but final mean plant heights were only 12, 8, 7, and 3 cm for the 4 planting dates, respectively. Only a limited amount of seed was set, and the yields from one harvest made on November 30th were only 0.11 and 0.08 g/M^2 for the first 2 planting dates, respectively. Data on emergence, plant growth and stands are summarized in Table 3 so that performance can be readily compared to that of the spring planting.

On October 3rd, a 500 foot row of *Cuphea wrightii* and a 500 foot row of *Lesquerella fendleri* were planted at the Yuma Mesa Agricultural Center concurrently with a direct seeded planting of guayule. Seed was planted with a Nibex 300 precision planter. The soil (Superstition sand) was a coarse-textured, low water-holding capacity sand. Irrigation water was applied with an automated, lateral-move sprinkler system. Germination and emergence of the Cuphea was good and stand counts averaged 41 plants per meter of row 11 days after planting. However, at this time, most of the seedlings showed a yellowing or bleaching of the cotyledonary leaves. Growth of seedlings were severely retarded and many of the plants were dying. The Lesquerella plants were showing similar symptoms and plant stand and growth appeared to be more severely affected. Essentially, no guayule plants could be found. The difficulty was later traced to an unexpected residual in the soil of a previously applied herbicide.

Lesquerella

On October 1, 1984, 1,632 plants from 54 accessions of 19 species of Lesquerella plus one accession of a species from a closely related genus (*Physaria floribunda*) were transplanted into the field at the Maricopa Agricultural Center and at the USWCL for evaluation and selection (Table 2). An additional direct seeded planting of 74 accessions of 18 species was also made at the same time at Maricopa. The plantings at Maricopa were made on 10-270 foot 40 inch beds, with 2 rows per bed. Transplanted plants were spaced 10 inches apart within the double rows, which were spaced approximately 14 inches apart on the bed. Such spacing provides a planting density of approximately 32,000 plants/acre (80,000 plants/hectare). The direct seeded plots were drilled with a Planet Jr. planter, two rows per bed in plots 25 feet (7.6 meters) in length. Emergence and stand counts were made periodically, and observations were made on general growth characteristics of the seedlings and transplanted plants. Large differences were observed in germination, emergence, and rate of survival among species and accessions within species. Total seedling stand counts for all accessions were 3,601 at 15 days after planting (DAP); 5,954 at 25 DAP and 2,395 at 50 DAP. Additional attrition is anticipated during the winter and spring months of 1985 before seed harvest in late spring. Stand count 50 DAP for transplanted plants also dropped to approximately 54%.

Germplasm Enhancement:

Cuphea

Seeds of putative hybrids involving Cuphea species within the section Heterodon have been obtained from crosses made at Phoenix and Tucson. In 1984 over 500 pollinations were attempted at Phoenix involving 14 cross combinations among 7 different species. A total of 82 seeds were obtained from 5 cross combinations (Table 4). This brings the total to 130 seeds obtained from 13 cross combinations involving 7 different species in 1983 and 1984. Germination of these seeds has been delayed until 1985 in an attempt to overcome dormancy. At Tucson over 1000 interspecific pollinations were made by Dr. Dennis Ray and Dr. Allen Gathman in 1984, resulting in 6 cytologically confirmed interspecific hybrid plants (2 - C. procumbens x C. leptopoda, and 4 - C. procumbens x C. lanceolata). Preserved buds from interspecific hybrids made by Dr. Shirley Graham, Kent State University, were also cytologically analyzed at Tucson. Three additional interspecific hybrids were confirmed from this material (C. lophostoma x C. lanceolata, C. procumbens x C. llavea var. hirta, and C. llavea var. hirta x C. llavea). The putative amphidiploid hybrid of C. wrightii x C. tolucana (A 0260 from Dr. Frank Hirsinger) was cytologically examined and shown to have an n chromosome number of 22. This raises an interesting question as to the origin of the hybrid since the n chromosome number of the parental species are C. wrightii (n=22) and C. tolucana (n=12). However, the hybrid has larger flowers and seed size and is otherwise morphologically distinct from either parental species. Steps are being taken to recreate this interesting hybrid combination. A total of 170 seeds from 6 new cross combinations made at Tucson will be grown out in 1985, and additional crosses will be attempted.

Methods have been developed and perfected at Tucson for fixing and staining Cuphea meiotic material. Acetocarmine squash preparations of meiotic anthers of 33 accessions of 14 species have been cytologically examined and characterized for chromosome number and chiasma frequency to assess the degree of chromosome pairing. This information is necessary to interpret cytogenetic data from current and future interspecific hybrids.

Selections of 53 rapidly germinating seedlings of 3 species--C. wrightii (33 plants from 2 accessions), C. tolucana (11 plants), and C. paucipetala (9 plants from 2 accessions) were made in an attempt to minimize seed dormancy. Self-pollinated seed was obtained from 51 of the plants and germinated. Thousand seed weights were also recorded (Table 5). A surprisingly high level of germination was obtained for some selections, ranging as high as 59% within 7 days after planting. A total of 590 (C. wrightii - 557; C. tolucana - 29: C. paucipetalla - 4) fast-germinating seedlings were selected and potted up from seed production and future testing. Data from individual plants are currently being taken on seed yield, seed weight, plant height and dry weight. Germination tests will be run on duplicate seed samples from each plant. In addition, oil percentages and fatty acid contents will be determined on individual plant progenies to assess the extent of intraspecific variability. Appropriate selections will be made and propagated for additional testing.

Attention has been given to locate and identify economically important genetic characters in Cuphea that may assist in the removal of production constraints. A compact plant growth character has been found in the species C. leptopoda. This new characteristic may prove useful in concentrating seed set. Research is in progress to determine its heritability and utility. The nonsticky mutant of C. procumbens (A 0263) obtained from Dr. Frank Hirsinger was observed to be segregating for a wide range of flower colors ranging from solid pinks, purples to reds, and various bicolor combinations. A clear, light pink selection has been made for possible use as a genetic marker. Crosses among plants with different flower color have also been initiated at Tucson to determine the inheritance of flower color in this species.

The cooperative research program at Purdue University conducted by Dr. Jules Janick has successfully developed in vitro culture methodology for the species C. wrightii through shoot tip and callus culture. This involves the production of organogenic callus from shoots and leaves and the direct proliferation of shoots. In vitro produced shoots have been successfully induced to produce roots. Such rooted plantlets have been successfully transferred to soil culture and production in the greenhouse. Such methods may lead to the possibility of screening large numbers of induced plantlets for somaclonal variation. Such variation may prove useful in removing genetic constraints to production such as seed shattering, dormancy, sticky plant hairs, and intermediate growth and flowering.

The cooperative program at Purdue is interested in expanding studies on the cell and tissue culture of Cuphea as an adjunct to germplasm enhancement and crop improvement, and to explore in vitro production of medium-chain fatty acids. These include the following techniques:

- Cell and protoplast culture and protoplast fusion technology.
- Anther culture of Cuphea to produce haploid cells and plants.
- Embryo culture, the induction of asexual embryogenesis, and the production of embryogenically-competent callus.

Liaison and Coordination of National Cuphea Research Program:

Liaison and coordination was provided for the national Cuphea research program, both within USDA/ARS and with universities and state agricultural experiment stations and with industry. Within the year, 3 site visits were conducted in Oregon to confer with research workers, discuss progress of the program, and inspect the experimental plots during the growing season. The dates of these visits were August 1 and 2 at Corvallis; August 15 to visit plots in Hermiston and Ontario in eastern Oregon; August 27-31 to attend, participate and present an overview of the USDA/ARS Cuphea Research Program at the 1984 Cuphea Research and Development Meeting at Corvallis; and December 5-8 to debrief Dr. Frank Hirsinger, who was leaving the program, and to discuss administrative and program matters with Oregon State University officials. In addition, the annual meeting of the Western Regional Project (W-157 "Development of New and Improved Crops for Water Conservation in Arid Lands") was attended on September 19-21 at Riverside, California.

Research on Cuphea and Lesquerella was reported along with other related research of the USWCL on guayule, guar, and runoff farming. On June 11-13 an invited paper entitled "New Native Crops for the Arid Southwest" was presented at the Society for Economic Botany Symposium on the "Ethnobotany of the Greater Southwest" at Texas A&M University, College Station, Texas. Research on Cuphea and Lesquerella was cited as examples.

SUMMARY AND CONCLUSIONS:

Cuphea:

Good progress has been made in many areas of research on Cuphea. The program has generated considerable interest within USDA/ARS, state universities and agricultural experiment stations, and industry. The cooperative aspects of the program are strongly developing, and the unique federal-state-industry funding mechanism may well serve as a model for future new crop R&D programs. Plans are being developed to increase the scope of the total program, and to increase the evaluation of germplasm for adaptation in other geographical areas. The 1984 field results designed to evaluate Cuphea germplasm for potential production in Arizona and the Southwest lead to the conclusion that few, if any, species of the genus are adapted to the high temperatures experienced throughout the growing season. Even though some plants continued to grow and flower, essentially no seed set was observed. Results also indicate that fall planting does not appear to be a viable option for production of Cuphea in this area. However, small-scale seed increase in the greenhouses appears feasible during the fall, winter, and early spring months.

The relatively high plant survival of the perennial species gives an indication that such material may be useful for production of a fall seed crop after high temperatures have abated. However, none of the perennial species in their present form appear to be directly adapted to agronomic culture. Considerable research in the area of germplasm enhancement and development would be needed to exploit the possible benefits of perennial growth habit for culture in the arid Southwest. To be useful, perennial germplasm will need to be developed that has a high potential for early, concentrated seed set and yield, with reduced shattering.

Indications are that much of the Cuphea germplasm currently being evaluated in the Oregon State program traces back to a limited number of collections from wild, native habitats. Steps are now being initiated to increase seed and distribute for evaluation all available accessions of agronomically promising species. Seed supply of most of these accessions is currently limited. These include *C. wrightii* (6), *C. laminuligera* (2), *C. leptopoda* (8), and *C. lutea* (2).

It is concluded that field experimentation should be limited at this location, and a major portion of the research on Cuphea be directed to germplasm enhancement and development of new sources of germplasm. Improved germplasm developed at this location will be made available for

evaluation and utilization at other locations encompassed within the national program. This project will also continue to have the responsibility for maintaining the Cuphea working germplasm collection and provide coordination and liaison within USDA/ARS, and with states and industry.

Lesquerella:

The prospects of successful domestication of Lesquerella species for production within the arid and semiarid Southwest are judged to be relatively high. Continued evaluation of the USDA/ARS Lesquerella working germplasm collection will be made within the plantings at Maricopa and the USWCL in Phoenix. Appropriate selections and seed increase of accessions will be made. Based upon current performance, new plantings will be made in the late fall at Maricopa and possibly at Yuma and Brawley for further evaluation.

REFERENCES:

None.

PERSONNEL:

A.E. Thompson, D.A. Dierig, and W.J. Allen

TABLE 1. CURRENT STATUS OF USDA/ARS CUPHEA GERMPLASM WORKING COLLECTION
U.S. WATER CONSERVATION LABORATORY-PHOENIX, AZ (JAN 1985)

SECTIONS OF GENUS & SPECIES	NUMBER OF SPECIES		GERMPLASM ACCESSIONS			
	RECEIVED/ KNOWN	SURVIVED/ RECEIVED	NUMBER RECEIVED	NUMBER SUCCESSFULLY GERMINATED	NUMBER WITH REMNANT SEED	NUMBER LOST
SUBGENUS CUPHEA:						
ARCHOCUPHEA:	0/3	-	0	-	-	-
CUPHEA:						
C. fruticosa			1	1	1	0
C. racemosa			4	2	4	0
C. salicifolia			2	0	1	1
TOTAL	3/17	3/3	7	3	6	1
SUBGENUS EUCUPHEA:						
HETERANTHUS:	0/10	-	0	-	-	-
MELICYATHIUM:	0/1	-	0	-	-	-
BRACHYANDRA:						
C. aperta			2	1	2	0
C. calophylla			3	0	3	0
C. carthagenensis			16	4	7	9
C. ferrisiae			1	0	1	0
C. vesiculigera			3	0	2	1
TOTAL	5/26	5/5	25	5	15	10
EUANDRA:						
C. diosmifolia		-	3	0	0	3
C. glutinosa			7	5	5	2
C. hyssopifolia		-	1	0	1	0
C. linariodes			2	2	1	1
C. linifolia			2	1	1	1
C. polymorphoides		-	2	0	0	2
C. pseudovaccinium		-	3	0	0	3
C. sclerophylla		-	1	0	0	1
C. thymoides			1	0	1	0
TOTAL	9/74	4/9	22	8	9	13
TRISPERMUM:						
C. ericoides		-	2	0	0	2
C. reflexifolia		-	2	0	0	2
TOTAL	2/16	0/2	4	0	0	4
PSEUDOCIRCAEA:						
C. lutescens			3	0	1	2
TOTAL	1/9	1/1	3	0	1	2

Table 1 (Cont.).

SECTIONS OF GENUS & SPECIES	NUMBER OF SPECIES		GERMPLASM ACCESSIONS			
	RECEIVED/ KNOWN	SURVIVED/ RECEIVED	NUMBER RECEIVED	NUMBER SUCCESSFULLY GERMINATED	NUMBER WITH REMNANT SEED	NUMBER LOST
HETERODON:						
C. angustifolia			2	2	2	0
C. calcarata			2	2	1	1
C. crassiflora			2	2	1	1
C. glossostoma			2	0	1	1
C. inflata			3	1	1	2
C. koehneana			3	2	3	0
C. laminuligera			4	3	3	1
C. lanceolata			29	29	28	1
C. leptopoda			11	5	9	2
C. llavea			14	4	9	5
C. lobophora		-	9	0	0	9
C. lophostoma			2	1	1	1
C. lutea			3	3	3	0
C. palustris			2	1	1	1
C. paucipetala			6	2	5	1
C. procumbens			19	18	16	3
C. quaternata		-	1	0	0	1
C. trochilus		-	1	0	0	1
C. tolucana			17	8	14	3
C. wrightii			18	6	9	9
C. wrightii x C. tolucana			2	2	2	0
C. viscosa		-	2	0	0	2
C. viscosissima			1	1	1	0
TOTAL	23/31	19/23	155	93	110	45
MELVILLA:						
C. caeciliae			1	1	1	0
C. heterophylla		-	7	0	0	7
C. ignea			5	2	4	1
C. jorullensis			2	0	1	1
C. melvilla			3	0	3	0
C. micropetala			3	0	3	0
TOTAL	6/36	5/6	21	3	12	9
LEPTOCALYX:						
C. aequipetala			6	2	6	0
C. bustimanta			1	0	1	0
C. calaminthifolia		-	1	0	0	1
C. graciflora			4	0	1	3
TOTAL	4/8	3/4	12	2	8	4
DIPLOPTYCHIA:						
C. cynea			4	1	1	3
C. hookeriana			9	8	8	1
C. nitidula			2	0	2	0
C. painteri			1	0	1	0
C. pinetorum			1	1	1	0
C. spectabilis			1	1	1	0
TOTAL	6/21	6/6	18	11	14	4
UNKNOWN:	?/?	?/?	7	0	7	0
GRAND TOTAL	59/252	46/59	274	125	182	92
PERCENT	23.4	79.0	-	45.6	66.4	33.6

TABLE 2. STATUS OF USDA/ARS LESQUERELLA GERMPLASM WORKING COLLECTION U.S. WATER CONSERVATION LABORATORY - PHOENIX, AZ (JAN. 1985)

SPECIES	GEOGRAPHIC SOURCE	PREDOMINANT HYDROXY FATTY ACID*	GERMPLASM ACCESSIONS: NUMBER RECEIVED	NUMBER GERMINATED	NUMBER WITH PLANTS IN FIELD PLOTS	NUMBER OF PLANTS IN FIELD (11/21/84): TRANSPLANTED	DIRECT SEEDED
L. angustifolia	SE OKLAHOMA & ADJACENT TEXAS	1	3	3	3	286	432
L. argyraea	SW. TEXAS TO NE NEW MEXICO	1	4	3	3	83	159
L. auriculata	OKLAHOMA & TEXAS	3	1	1	1	45	255
L. densipila	TENNESSEE	2	3	2	2	22	5
L. engelmannii	W. OKLAHOMA TO CENTRAL TEXAS	1	4	4	2	7	39
L. fendleri	SE. ARIZONA TO W. TEXAS, SW. COLORADO TO N. CENTRAL MEXICO	1	26	25	24	107	708
L. globosa	KENTUCKY & N. TENNESSEE	1	1	0	0	0	0
L. gordonii	SE. ARIZONA TO W. TEXAS & W. OKLAHOMA, N. CENTRAL MEXICO	1	26	25	25	26	308
L. gracilis	CENTRAL OKLAHOMA & TEXAS	1	3	3	3	66	337
L. grandiflora	S. CENTRAL TEXAS	1	2	2	2	84	72
L. lasiocarpa	S. TEXAS & NE. MEXICO	1	2	2	2	22	4
L. lescurii	CENTRAL TENNESSEE	2	1	1	0	0	0
L. lindheimeri	E. TEXAS	1	1	0	0	0	0
L. ludoviciana	WYOMING	1	1	1	1	18	0
L. lyrata	ALABAMA	2	1	1	1	5	0
L. mirandiana	MEXICO	?	1	1	0	0	0
L. ovalifolia	W. OKLAHOMA & KANSAS, SE. COLORADO, N. TEXAS, NE. NEW MEXICO	1	1	1	0	0	0
L. palmeri	CENTRAL ARIZONA	1	2	2	2	2	4
L. perforata	TENNESSEE	2	2	2	2	19	4
L. pinetorum	CENTRAL NEW MEXICO	1	1	1	1	13	15
L. purpurea	E. CENTRAL ARIZONA	1(?)	1	1	1	26	33
L. recurvata	?	?	1	0	0	0	0
L. stonensis	TENNESSEE	2	2	2	2	23	5
L. spp.	------	?	2	2	2	24	15
Physaria floribunda	NEW MEXICO	1	1	1	1	2	0
TOTAL			93	86	80	880	2,395

* 1 = Lesquerolic acid (14-hydroxy-*cis*-11-eicosenoic acid)
2 = Densipolic acid (12-hydroxy-*cis*-9, *cis*-15-octadecadienoic acid)
3 = Auricolic acid (14-hydroxy-*cis*-11, *cis*-17-eicosadienoic acid)

TABLE 3. GROWTH PERFORMANCE OF CUPHEA WRIGHTII DIRECT SEEDED PLANTINGS - SPRING & FALL, 1984. MARICOPA AGRICULTURAL CENTER

GROWTH PARAMETERS	SPRING PLANTING	FALL PLANTING 1	2	3	4
DATE OF PLANTING:	4/20	8/27	9/4	9/14	9/24
EMERGENCE:					
DAYS TO EMERGENCE	11	7	6	7	7
NO. OF SEEDLINGS*	15	66	25	17	9
2-LEAF STAGE:					
DAYS AFTER PLANTING	31	14	13	14	15
NO. OF SEEDLINGS*	49	54	45	21	20
6-LEAF STAGE:					
DAYS AFTER PLANTING	39	28	27	25	28
NO. OF SEEDLINGS*	-	62	40	20	12
PLANT HEIGHT (cm)	1.8	5.8	5.5	3.4	1.8
BRANCHING STAGE:					
DAYS AFTER PLANTING	46	35	35	31	37
NO. OF SEEDLINGS*	-	57	38	19	8
FLOWERING STAGE:					
DAYS AFTER PLANTING	56	43	41	40	44
NO. OF SEEDLINGS*	39	52	36	10	5
PLANT HEIGHT (cm)	8.4	9.3	7.7	4.2	2.2
RIPENING STAGE:					
DAYS AFTER PLANTING	72	58	57	61	68
NO. OF SEEDLINGS*	25	48	29	7	4
PLANT HEIGHT (cm)	21.9	12.0	7.7	7.3	2.6

* Number of seedling plants per meter of row.

TABLE 4. CUPHEA INTERSPECIFIC CROSSES ATTEMPTED - 1984

PARENTAL SPECIES FEMALE PARENT	x MALE PARENT	FLOWERS POLLINATED (NO.)	FLOWERS WITH SEED SET NO.	FLOWERS WITH SEED SET %	SEEDS OBTAINED (NO.)
C. angustifolia	C. laminuligera	10	0	0	0
C. angustifolia	C. leptopoda	10	0	0	0
C. lanceolata	C. angustifolia	1	0	0	0
C. procumbens	C. angustifolia	34	1	2.9	10
C. crassiflora	C. laminuligera	35	1	2.9	2
C. crassiflora	C. leptopoda	19	0	0	0
C. laminuligera	C. leptopoda	34	0	0	0
C. leptopoda	C. laminuligera	277	18	6.5	60
C. leptopoda	C. llavea	12	1	8.3	1
C. leptopoda	C. procumbens	25	0	0	0
C. procumbens	C. leptopoda	9	0	0	0
C. procumbens	C. laminuligera	33	0	0	0
C. llavea	C. laminuligera	12	0	0	0
C. llavea	C. procumbens	5	4	80.0	9
TOTAL		516	25	4.8	82

TABLE 5. SELECTION FOR RAPIDITY OF GERMINATION - EMERGENCE OF PROGENY OF SELECTED SEEDLINGS. SEED PLANTED 9/24/84.

PEDIGREE NUMBER	NUMBER OF SEEDS OBTAINED	NUMBER OF SEEDS PLANTED	1000 SEED WEIGHT (g)	GERMINATION % 7 DAP*	GERMINATION % 11 DAP*	GERMINATION % 16 DAP*	PLANTS SELECTED (%)
C. WRIGHTII:							
0255-1	101	100	2.46	29.0	31.0	-	31.0
-2	64	64	2.35	57.8	57.8	-	57.8
-3	23	23	2.20	8.7	21.7	-	21.7
-4	96	96	2.59	20.8	27.1	-	27.1
-5	62	62	2.51	37.1	48.4	-	48.4
-6	34	34	2.59	58.8	58.8	-	58.8
-7	42	42	2.56	50.0	54.8	-	52.4
-8	8	8	2.71	37.5	37.5	-	37.5
-9	25	25	2.55	20.0	40.0	-	32.0
-10	14	14	2.33	21.4	42.9	-	28.6
-11	89	89	2.66	34.8	42.7	-	37.1
-12	36	36	2.71	44.4	50.0	-	50.0
-13	19	19	2.57	52.6	52.6	-	52.6
-14	135	100	2.52	44.0	44.0	-	40.0
-15	126	100	2.18	4.0	4.0	-	4.0
-16	1	1	2.50	0	0	-	0
-17	0	0	-	-	-	-	0
-18	144	100	2.55	8.0	10.0	-	9.0
-19	61	61	2.64	41.0	45.9	-	42.6
-20	81	81	2.16	42.0	45.7	-	42.0
-21	72	72	2.54	29.2	34.7	-	29.2
TOTAL	1233	1127	-	356	403	-	381
MEAN ($\bar{x}$)	-	-	2.495	31.59	35.76	-	33.81
0261-1	218	100	2.47	21.0	24.0	-	22.0
-2	481	100	1.97	20.0	30.0	-	22.0
-3	125	100	2.63	14.0	20.0	-	15.0
-4	455	100	2.13	13.0	15.0	-	14.0
-5	381	100	2.01	4.0	9.0	-	5.0
-6	304	100	2.33	16.0	21.0	-	16.0
-7	359	100	2.07	25.0	27.0	-	23.0
-8	370	100	2.09	17.0	20.0	-	17.0
-9	301	100	1.97	4.0	8.0	-	4.0
-10	344	100	2.37	10.0	10.0	-	10.0
-11	60	60	2.54	23.3	31.7	-	21.7
-12	335	100	1.89	18.0	22.0	-	15.0
TOTAL	3733	1160	-	176	225	-	176
MEAN ($\bar{x}$)	-	-	2.204	15.17	19.40	-	15.17
C. TOLUCANA:							
0262-1	678	100	1.10	0	0	0	0
-2	195	100	0.90	0	0	0	0
-3	1027	100	1.17	0	1.0	2.0	2.0
-4	885	100	1.11	1.0	1.0	1.0	1.0
-5	983	100	1.12	1.0	3.0	4.0	4.0
-6	724	100	1.07	0	0	6.0	6.0
-7	766	100	1.20	0	0	0	0
-8	173	100	0.95	0	0	0	0
-9	758	100	1.06	0	3.0	6.0	6.0
-10	421	100	1.06	4.0	8.0	10.0	10.0
-11	260	100	1.06	0	0	0	0
TOTAL	6870	1100	-	6	16	29	29
MEAN ($\bar{x}$)	-	-	1.074	0.55	1.45	2.64	2.64
C. PAUCIPETALA:							
0253-1	240	100	1.80	1.0	1.0	1.0	1.0
-2	468	100	1.77	0	0	0	0
-3	210	100	1.74	0	0	0	0
-4	227	100	1.90	0	0	0	0
-5	285	100	1.80	0	0	0	0
-6	212	100	1.77	0	0	0	0
-7	284	100	1.75	0	0	0	0
TOTAL	1926	700	-	1	1	1	1
MEAN ($\bar{x}$)	-	-	1.789	0.14	0.14	0.14	0.14
0259-1	481	100	1.82	0	2.0	3.0	3.0
-2	0	0	-	-	-	-	-
TOTAL	481	100	-	0	2	3	3
MEAN ($\bar{x}$)	-	-	1.817	0	2.00	3.00	3.00

* DAP = Days after planting.

TITLE: TRICKLE AND LEVEL BASIN IRRIGATION OF COTTON ON A SANDY LOAM SOIL

NRP: 20160 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

One of the greatest challenges confronting farmers in the southwestern United States is striking a balance between limited water supplies and obtaining higher yields. Precise information on crop water requirements and on the effects of water deficits on crop yield and quality are needed before irrigation efficiencies can be increased. Recently, growers and researchers have reported cotton lint yields of more than 2250 kg/ha (2000 lb/ac, 4 bales/ac) using trickle irrigation (Taylor *et al.*, 1983). An economic report indicated that if water deliveries were at a minimum and yield were raised by 280 kg/ha (250 lb/ac) or more, trickle irrigation of cotton could be profitable (Wilson *et al.*, 1984). Because of the interest in improving water use efficiencies and achieving maximum yields on cotton, an extensive irrigation study was conducted in 1984. The objective was to determine the effects of irrigation water placement and frequency for trickle and level-basin irrigation methods under optimum moisture conditions for conventional and narrow-row plantings using the newer short-stable cotton varieties.

Field Procedures:

Cotton varieties of DPL-61, DPL-90, DPL-41, and Stoneville 825 were planted on the conventional 1.0 m (40 in) row spacing on April 11, 1984 at the Maricopa Agricultural Center, University of Arizona, on a sandy loam soil. At the same time DPL-61, DPL-90, DPL-30 and DPL-70 were planted on the narrow-row, 0.75 m (30 in) row spacing in a mulch after a preplant irrigation. An excellent stand was obtained on the conventional planting; however, the seed germination was inadequate for research purposes on the narrow-row planting because of cold temperatures and rapid drying on the smaller beds. The narrow-row planting was replanted on May 2, and establishment was excellent. Each treatment plot was 10 m (33 ft) long and consisted of 24 rows with 6 rows of each of the four different varieties, as shown in Figure 1. The varieties were randomized within the five irrigation treatments which were replicated six times.

The five irrigation treatments 1984 were as follows: (1) a single trickle irrigation line per two cotton rows irrigated daily; (2) a single trickle line per two cotton rows irrigated twice weekly; (3) a single trickle line per three cotton rows irrigated daily; (4) level-basin irrigated weekly; and (5) level-basin irrigated biweekly (every two weeks). Irrigation scheduling was based on historical (Erie *et al.*, 1982) and meteorological estimates of evapotranspiration with conventional and narrow-row cotton receiving the same water applications. Regular irrigation treatments commenced on June 4 and continued through September 16. Soil water was measured weekly on three replicates to a 1.8 m (6 ft) depth with neutron moisture meters on treatments 1, 4, and 5 for DPL-61 and DPL-90 varieties. Treatment 1 was monitored to show

placement and uniformity of soil water contents, whereas treatments 4 and 5 were used for estimating the water consumed by the cotton crop.

The trickle line used was the Irridelco[1/] system with in-line 2L/h (0.5 gal/h) emitters placed 1.0 m (40 in) apart along the line. The water supply was from two farm wells and was filtered through sand filters followed by a screen filter with 74 micron (200 mesh) openings. The electrical conductivities of the two wells were about 1.1 dS/M (690 mg/l) and a 3.2 dS/M (2070 mg/l) respectively. About one half of the water applied was from each well. The irrigation water applied was measured through household, 2 cm (0.75 in) diameter, propeller-type water meters. The furrow plots were irrigated by delivering water through a 15 cm (6 in) main line followed by 5 cm (2 in) lateral lines going to the individual plots. Water applied was measured through a 10 cm (4 in) diameter, propeller-type water meter for all furrow irrigations.

Fertilizer applications were made through both irrigation systems in the form of liquid UN_{32}. A total of 269 kg/ha (240 lbs N/ac) was applied at a rate of 34 kg (30#) of N per week over an eight week period beginning on June 18 and finishing on August 10. Cotton leaf petiole samples were taken beginning on June 8, continued every two weeks through September, and analyzed for nitrate-nitrogen. In addition, the soil was sampled in late November to a 120 cm (4 ft) depth and analyzed for pH, nitrates, and total dissolved salts.

A Bioregulator compound 2-(3,4-dichlorophenoxy) - triethylamine [DCPTA] was also sprayed on May 15, 22, and 29 at the 3, 5, and 8 leaf stages on the conventional row spacing and on June 1, 8, and 15 at the same growth stages on the narrow-row spacings for DPL-61 and 90 varieties. The bioregulator spray formulation included 0.1% Ortho X-77 spreader (Chevron Chemical Co. [1/]), 100 mg/l of 2-diethylaminoethanol, and 50 ml/l isopropanol as a wetting agent. Two concentrations of bioregulators at 125 mg/l and 25 mg/l plus the wetting agent alone were sprayed with about 800 ml of solution being applied per spraying date on single-row plots 4.6 m (15 ft) long located alongside buffer rows. The application rates then totaled about 0.88 kg/ha (0.78 lb/ac) and 0.18 kg/ha (0.16 lb/ac) on the conventional row spacings and 1.1 kg/ha (1.0 lb/ac) and 0.25 kg/ha (0.22 lb/ac) on the narrow row spacings in terms of actual bioregulator chemical applied on the high and low concentration sprayings.

The cotton field was defoliated in early and late October; however, late season rains delayed harvesting until November and December. From November 12-16, cotton was handpicked from 3.0 m (10 ft) rows on DPL-61 and 90 varieties for the bioregulator, wetting agent, and check treatment. On December 18, two rows 9.1 m (30 ft) long were harvested from the 6 row plots for all varieties and row spacings on treatments 1, 2,

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[1/] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by the U.S. Department of Agriculture.

4, and 5, except three rows were harvested for treatment 3 (a single trickle line per three cotton rows irrigated daily).

RESULTS AND DISCUSSION:

The total amount of water applied plus rainfall on trickle and level-basin irrigation methods averaged 855 mm (34.8 in) and 860 mm (33.9 in), respectively, as shown in Table 1, after about 150 mm (5.9 in) of water was stored within the root zone from preplant irrigations. The number of irrigations ranged from 90 on the daily trickle (treatment 1) to 8 on the biweekly level-basin practice (treatment 5). The 1984 consumptive water use for cotton averaged 830 mm (32.7 in) on treatment 4 and 725 mm (28.5 in) on treatment 5 with semi-monthly values shown in Figure 2 and 3 for DPL-61 and 90 varieties. These seasonal consumptive use values as measured by the soil water depletion method were nearly the same for conventional and narrow-row plants, but were considerably less than previously reported estimates (1045 mm, 41.2 in) for older cotton varieties in central Arizona. Lower daytime temperatures, higher relative humidity and increased cloud cover accounted for some of the reduction in the 1984 evapotranspiration rates.

Leaf petiole samples taken throughout the growing season (Table 2) indicated that an adequate nitrogen supply was available to the cotton plants and that a similar nitrogen use pattern with time resulted for the two row spacings, different varieties, and various irrigation treatments. Although nitrate-nitrogen levels may have been somewhat low in late June, they recovered quickly in early July so that leaf petiole concentrations of more than 10,000 mg/l existed on all treatments by July 14. Soil salinity was moderate and residual soil nitrogen was adequate at the end of the cotton experiment (Table 3).

Hand-picked cotton yields from rows treated with bioregulator, wetting agent only, and the control area were generally the same regardless of the treatment on both row spacings (Table 4). Visual observations were that the bioregulators had little effect on plant height, boll set, or number of bolls. Although bioregulators have exhibited dramatic effects in the greenhouse, the type of bioregulator used in this field experiment was not effective at the two application rates. Average lint yields from the hand picked plots in mid-November (Table 4) were similar to the larger machine picked plots on December 18 (Table 5).

A maximum lint yield of 2540 kg/ha (2265 lb/ac, 4.5 bales/ac) was achieved for the DPL-90 variety with the single trickle irrigation line per every two rows irrigated daily (treatment 1) on the conventional row spacing, as shown in Table 5. Cotton grown on the 1.0 m spacing produced about 15% more lint yield when a single trickle line per two cotton rows was used rather than the level-basin irrigation method, and cotton lint yields were reduced by 33% for a single trickle line per three cotton rows (treatment 3, 3.0 m water placement distance) compared with a single trickle line per two rows (treatment 1, 2.0 m distance). On the other hand, there was little yield difference between the two irrigation methods for the narrow-row plantings. However, the single trickle line per three cotton rows irrigated daily (treatment 3) showed

considerable promise where the lateral lines were 2.3 m (90 in) apart or narrow rows rather than 3.0 m (120 in) on the conventional row spacings.

For both row spacings, the weekly level-basin irrigation treatment outyielded the biweekly schedule by about 170 kg/ha (150 lb/ac) on the variable, sandy loam soil (Table 6). Also, cotton lint yields were about 100 kg/ha (90 lb/ac) higher on the daily versus twice weekly trickle irrigations, particularly on the conventional row spacing, indicating that the more frequent irrigations were advantageous for the conditions of this experiment. Varietal response showed that the DPL-90 was the best for the conventional row spacings, whereas DPL-70 was adapted to the narrow-row spacing.

Field studies on cotton using trickle and level-basin irrigation methods will be repeated in 1985 with emphasis on the effects of water placement, irrigation frequency, conventional and narrow-row production, and newer cotton varieties. Since DPL-61 was the lowest producer on both row spacing, we plan to replace it with the experimental DPL-775. A manuscript will be prepared for presentation at the Third International Drip/Trickle Irrigation Congress in 1985.

SUMMARY AND CONCLUSIONS:

Both trickle and level-basin irrigation methods, when properly managed and operated, have a potential to achieve high cotton yields and water use efficiencies on a marginal soil. A maximum lint yield of 2540 kg/ha (4.5 bales/ac) was achieved for the DPL-90 variety with the single trickle irrigation line per every two rows irrigated daily on the conventional row spacing. Narrow-row plantings may not always increase yields over conventional plantings; however, light-frequent irrigations can be beneficial where the uniformity of water applications is high. Water placement from a trickle irrigation line can be as much as 2.3 m (90 in) apart, but a 3.0 m (120 in) distance was not adequate for the coarse-textured soil. Some of the newer cotton varieties appear to have a lower water requirement than the varieties planted 10 years ago in the arid Southwest and are more adaptive to frequent irrigations. No significant yield increase resulted from the use of a promising bioregulator compared to the nontreated cotton plants suggesting that additional field studies are needed.

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Table 1. Water applied as irrigation water plus rainfall with trickle and level-basin irrigation systems, 1984.1/

Irrigation Treatment2/	No. of Irrigations	Total Water Applied (mm) 1.0 m Furrows	Total Water Applied (mm) 0.75 m Furrows
1	90	881	881
2	30	887	887
3	90	885	891
4	14	887	852
5	8	808	855

1/ Rainfall totaled 214 mm (8.4 in) throughout the growing season.
2/ Irrigation treatments are listed in procedures.

Table 2. Average cotton petiole analyses for Nitrate-Nitrogen (mg/l) with time in 1984.1/

		Sampling Dates								
Spacing	Variety	6/8	6/25	7/9	7/23	8/6	8/20	9/4	9/17	10/4
	DPL-61	10100	6800	9200	11000	8600	5100	2000	1700	500
1.0 m	DPL-90	12200	6800	9200	10200	7800	4900	1800	1500	400
	DPL-41	12700	7900	9800	11200	9500	5900	2200	1900	450
	Stone. 825	12200	5500	8500	11300	8500	6100	2500	2200	500
	DPL-61	9900	6600	8800	8900	7800	4300	2000	1600	300
0.75 m	DPL-90	11900	7300	9100	10000	8200	4300	2000	1800	350
	DPL-30	10000	6600	10600	9700	7500	4000	2200	1900	600
	DPL-70	12100	7600	9300	8800	7400	4500	2200	1900	450

1/ Each number represents mean of 5 irrigation treatments and 3 replications.

Table 3. Soil analysis in late November for the 1984 cotton experiment.

	Soil Depths (cm) 0-5	0-30	30-60	60-0	90-120
pH	7.3	7.5	7.4	7.5	7.2
Total Dissolved Salts (g/m^3)	1046	1572	1633	1736	1176
Nitrate (mg/l) Nitrogen	66.1	89.9	101.3	100.6	78.0

Table 4. Average cotton yields for DPL-61 and 90 varieties as affected by bioregulation and/or wetting agent from handpicked plots in mid-November 1984.

Row Spacing	Treatment	Seed Weight (g/plot)2/	Lint Percent2/	Lint Weight (g/plot)2/	Lint Yield (kg/ha)3/
Conventional 1.0 m	Bioregulator1/	1530	39.2	600	1935
	Wetting Agent	1612	39.7	640	2065
	Control	1525	39.0	595	1920
	Mean	1555	39.3	612	1973
Narrow Row 0.75 m	Bioregulator	1289	40.5	522	2250
	Wetting Agent	1416	38.5	545	2310
	Control	1421	39.0	554	2385
	Mean	1375	39.3	540	2315

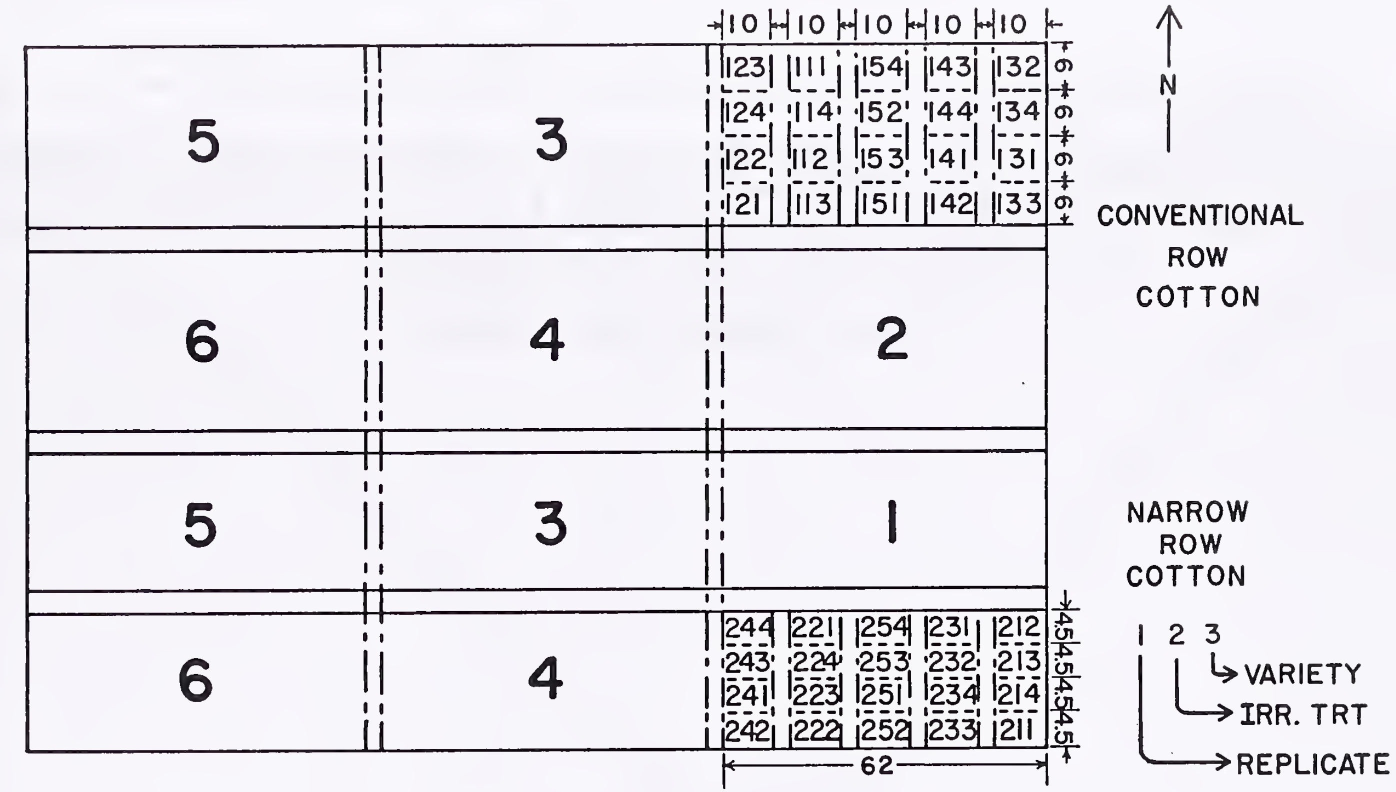
1/ DCPTA plus wetting agent.
2/ Each number represents a mean of 6 replicates.
3/ 560 kg/ha = 1.0 bale/ac.

Table 5. Average lint cotton yields for trickle and level-basin irrigation methods from machine picked plots on December 18, 1984.

Row Spacing	Cotton Variety	Irrigation Treatment 1/ 1	2	3	4	5	Mean
		Lint Yield (kg/ha)2/					
Conventional 1.0 m	DPL-61	2065	2115	1595	1870	1845	1898
	DPL-90	2540	2365	1605	2220	2180	2182
	DPL-41	2315	2285	1500	2125	1710	1984
	Stoneville 825	2355	2110	1400	2165	1895	1985
	Mean	2318	2218	1525	2095	1908	2013
Narrow Row 0.75 m	DPL-61	1830	1885	1945	1805	1705	1834
	DPL-90	1800	1870	1980	1920	1815	1877
	DPL-30	2185	1985	2025	2150	1955	2060
	DPL-70	2317	2290	2380	2420	2190	2320
	Mean	2033	2008	2083	2074	1916	2023

1/ Irrigation treatments are listed in procedures; each number represents a mean of 6 replicates.
2/ 560 kg/ha = 1.0 bale/ac; lint percentage averaged 39.5% on the conventional and 38.4% on the narrow-row plantings.

1984 COTTON EXPERIMENT-MARICOPA AGRICULTURAL CENTER



* All measurements in meters

Irrigation Treatments

1. A single trickle line per two cotton rows irrigated daily.
2. A single trickle line per two cotton rows irrigated twice weekly.
3. A single trickle line per three cotton rows irrigated daily.
4. Every furrow with the level-basin method irrigated weekly.
5. Every furrow with the level-basin method irrigated bi-weekly.

Varieties	
1. DPL-61	1. DPL-61
2. DPL-90	2. DPL-90
3. DPL-41	3. DPL-30
4. STONE.825	4. DPL-70
1.0 m rows	0.75 m rows

Figure 1. Planting diagram for 1984 cotton experiment at the Maricopa Agricultural Center, Maricopa, AZ.

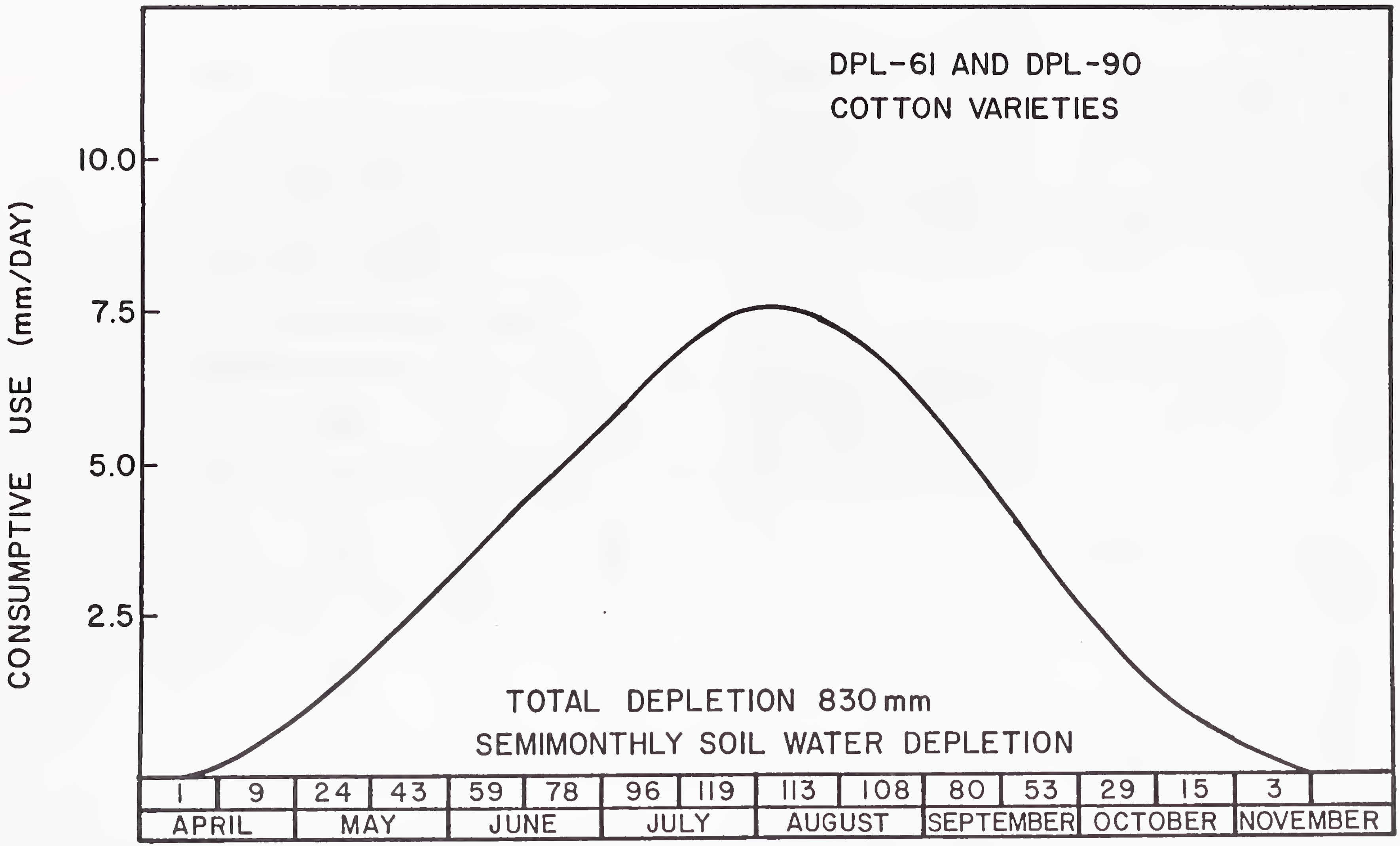


Figure 2. Mean Soil water depletion curve for cotton irrigated weekly at the Maricopa Agricultural Center, Maricopa, AZ, 1984.

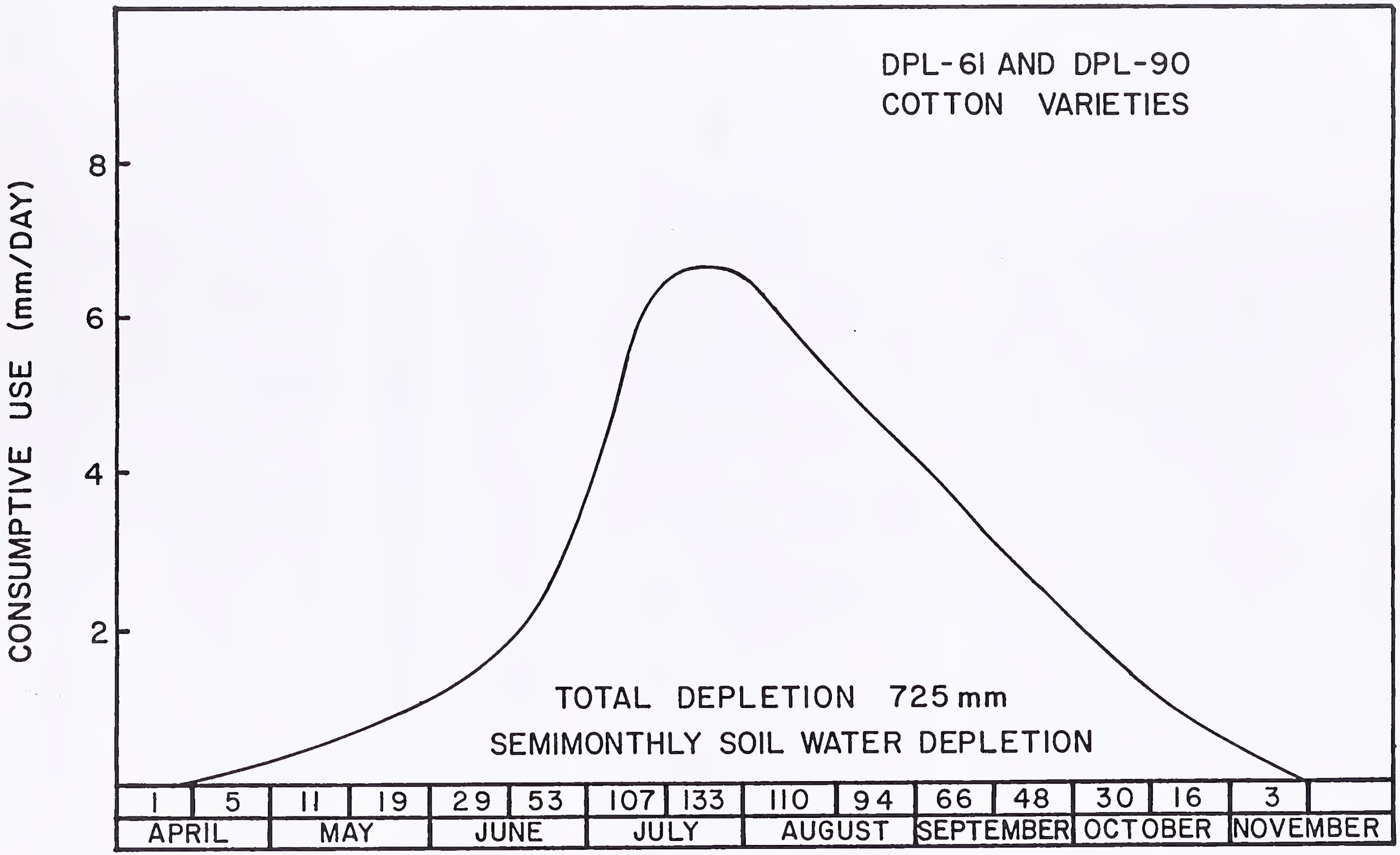


Figure 3. Mean Soil water depletion curve for cotton irrigated biweekly at the Maricopa Agricultural Center, Maricopa, AZ, 1984.

TITLE: BORDER IRRIGATION UNIFORMITY: COMBINED EFFECTS

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION:

The uniformity at which water can be distributed over a field can have a direct impact on the potential irrigation efficiency when irrigations are intended to fully meet consumptive use or on yields when deficit irrigation is practiced. Thus it is of interest to know the uniformity of distribution of the irrigation water for any irrigation system. For surface irrigation systems, there are a number of factors which influence this uniformity. These include variations in opportunity time, variations in soil infiltration characteristics, variations in surface retention after recession caused by a nonplane field surface, variations in furrow wetted perimeter caused by flow depth variations, variations in inflow rate and cutoff times between irrigation sets, etc. The first two of these are the dominant causes of nonuniformity in many cases, and are the topic of this paper.

For any type of surface irrigation system, differences in opportunity time occur because of fundamental differences in the shapes of the advance and recession curves. Irrigation engineers have long studied opportunity times as a means of measuring uniformity and irrigation effectiveness. Even for uniform opportunity times, infiltrated amounts will vary over the field due to differences in soil conditions. Soil Scientists have recently increased research efforts on the spatial variations of infiltration. However, little has been done on how this variation affects irrigation design and operation. The purpose of this paper is to develop methods for combining the effects of variations in opportunity time and spatial variations in infiltration. These methods can then be used in the design and management of irrigation systems.

Uniformity:

A variety of terms have been used to describe irrigation uniformity. One of the most useful of these terms is the low quarter distribution uniformity

$$DU_{1q} = \frac{\text{Average depth of lowest quarter of area}}{\text{Average depth of total area}} \qquad (1)$$

DU_{1q} can be related to yield when the lowest 1/4 of the field is underirrigated, the yield response to deficits is linear, and there is no yield response to over irrigation. DU_{1q} can be related to deep percolation losses (and thus irrigation efficiency) when the numerator is the desired application depth. Thus DU_{1q} is a useful uniformity measure. For a normal distribution of depths, DU_{1q} can be determined from the coefficient of variation, CV, by

$$DU_{1q} = 1 - 1.27CV \qquad (2)$$

where CV = standard deviation of infiltrated depths divided by the average infiltrated depth.

In general, opportunity times in surface irrigation are not normally distributed, as will be demonstrated herein. Spatial variations in infiltration are also probably not normally distributed. Within close distances, soil properties are supposedly similar. However, for soils farther apart than about 10 to 30 m, properties are independent or random and thus normally distributed. This assumes that any trends in soil properties have been removed. For now, trends will be ignored and will be studied in more detail at a later date.

It will be assumed that infiltration is of the form

$$D = kt^a \tag{3}$$

where D is the cumulative infiltrated depth over time t and k and a are empirical constants. It is further assumed that the exponent a does not vary spatially. In general, variations in a are not as significant as variations in k. Infiltration data from multiple ring infiltrometers often show similar slopes on log-log plots of z vs t, where a is the slope. It is recognized that this straight-line power function is only valid within a limited range of infiltration. It is however reasonable for this analysis.

With the above assumptions, the variations in depth can be separated into two terms; k and t^a. Variations in k are then related to soil spatial variations and variations in t^a are related to variations in infiltration opportunity time. Now if the variations in these two variables are independent, then the expected value of the total variation in terms of the coefficient of variation CV_D can be described by

$$CV_D = \sqrt{CV_h^2 + CV_k^2 + CV_h^2 CV_k^2} \tag{4}$$

where CV_h is the coefficient of variation of the resultant opportunity time distribution in terms of t^a and CV_k is the coefficient of variation caused by soil variation in terms of k. This equation is valid for any two distribution types for t^a and k provided that the distributions are independent. CV_D is the expected value of the total variance. Actual values for a specific site will vary from this.

Except for special cases, the form of the resulting distribution is not known. This makes evaluating distribution uniformity or any other performance parameter difficult. If both distributions are normally distributed, the resulting distribution will be normally distributed. Then by knowing the coefficients of variations CV_h and CV_k, one could find CV_D from Equation (4) and DU_{1q} from Equation (2). However, the distribution of t^a is in general not normally distributed. In an earlier work (Clemmens, 1985), I developed a method for estimating DU_{1q} with Equations (2) and (4) when one of the distributions is not normally distributed. The method is based on finding an equivalent CV for the non-normal distribution that would give the correct DU_{1q} for that distribution. The procedure would be as follows for a non-normal distribution of t^a.

1. Compute the distribution of t^a.
2. Compute DU_{1q} for t^a from Equation (1) (more precisely with D from Equation (3) with k = 1).
3. Compute an equivalent or back calculated CV_h from DU_{1q} above and Equation (2).
4. Determine CV_k for given soil.
5. Compute CV_D from Equation (4).
6. Compute DU_{1q} from Equation (2).

For trickle irrigation simulation with variations in pressure and emitter characteristics and a discharge relationship similar to Equation (3), this procedure when compared to the average value from simulation was within ± 1.1%. In a later section, this procedure will be examined for a surface irrigation simulation.

Clemmens (1985) indicated that for trickle irrigation that pressure variations were essentially independent of variations in emitter discharges from the mean. Jaynes and Clemmens (1985) indicate that for low values of CV_h and large values of CV_k that the opportunity time variations in terms of t^a and the soil variations in infiltration in terms of k were independent when soil variability was assumed normally distributed. This independence assumption needs to be further examined for the cases where CV_h is relatively large compared to CV_k, where trends exist in the soil variation, and where the soil variation has spatial dependence. When soil variations are large, the stream advance may be slowed or sped up from that with uniform conditions. Also when trends exist, the distribution of depth will undoubtedly change depending on how the infiltration trends match up with the opportunity time trends. When one or both distributions are somewhat random this is not a factor. When both have trends, then it is a factor. For the analysis presented here, independence is assumed. Further work will have to be done to test these independence assumptions.

Simulations for Level Basins:

Simulation runs were made to test the suitability of Equations (2) and (4) and the procedure presented for back calculating DU_{1q} for estimating the DU_{1q} of a surface irrigation system. Level basins were chosen for this analysis since simulation of opportunity times is simplified by an assumed uniform recession time. Stream advance distance is assumed to be an exponential function of time with exponent h. The opportunity time is simply the difference between the advance time and recession time. In an earlier work (Clemmens, 1981), it was shown that the distribution of opportunity times could be defined by the exponents h and a from the advance and infiltration equations respectively and the ratio of the advance time to the minimum opportunity time (at the end of the basin). The inverse of this ratio is often called the advance ratio, AR. Thus a, h and AR are sufficient to develop a distribution of opportunity times.

For the purposes of this analysis, a and h were arbitrarily set to 0.6. Then AR was adjusted to develop values of CV_h of 0.05 to 0.25 by steps of 0.05. Values for 1/AR were 0.33, 0.81, 1.57, 2.93 and 5.80 for CV_h from 0.05 to 0.25, by 0.05, respectively. The field length was broken into 100 segments, with each segment assigned a value for opportunity

time. With k set arbitrarily to unity, the distribution of depths was calculated from Equation (3) and used to calculate DU_{lq} for the opportunity time distribution alone from Equation (1). Next a back calculated CV_h was found from Equation (2) for later analysis. These calculations were made for each value of CV_h.

Next, the infiltration constant k was allowed to vary with a Monte Carlo simulation. Values of k were randomly assigned to each segment of field length for a given value of CV_k. These k values were adjusted to give the correct overall mean. This was repeated 100 times for each CV_k value and was run for CV_k values from 0.05 to 0.25 by steps of 0.05. For each combination of CV_h and CV_k, DU_{lq} was computed from Equations (2) and (4) for assumed normal distributions, DU_N. A back calculated DU_{lq}, DU_{BC}, was computed from Equations (2) and (4) with the back calculated CV_h. A simulated DU_{lq}, DU_S, was computed from Equation (2) with the average CV_D value from the 100 simulation runs for each CV_k, CV_h combination. An actual DU_{lq}, DU_A, was computed as an average from the actual depths from the 100 simulation runs. The standard deviation of DU_A, S_{DU}, was also computed to determine the magnitude of the variation in DU_{lq} from the average or expected value. Thus the results of the simulation run include DU_N, DU_{BC}, DU_S, DU_A and S_{DU}. These results are given in Table 1.

RESULTS:

Column 3 of Table 1 shows the DU_{lq} for assumed normal distributions. In all cases, the last term in Equation (4) was dropped according to the recommendations by Bralts et al. (1981). The actual simulation results are given in column 6. The difference between columns 3 and 6 is given in column 8. While the differences are not too large, the results clearly indicate that the hydraulic distribution is not normally distributed. For large CV_h and small CV_k, DU_N predicts higher uniformities than are actually attained (eg. CV_h=85% and CV_k=5% gives an error of +4.2). For small CV_h and large CV_k, DU_N predicts lower uniformities, but generally the differences are much lower. Thus for small CV_h, a combined normal distribution is not too unreasonable, as was found by Jaynes and Clemmens (1985).

Column 5 of Table 1 shows the DU_{lq} from Equation (2) for the actual average CV_D from the simulation. Only minor differences are noted between columns 3 and 5, usually being less than 1/2%. Some of the differences are due to the dropping of the last terms in Equation (4) in the calculation of DU_N. However, in many cases, dropping the term actually improved the prediction of DU_N. For example, at CV_h=25%, CV_k=25%, DU_A=55.4, DU_N=55.1 while with the last term added DU_N=54.4. With DU_S=54.3, the CV_D from simulation is in correspondence with Equation (4). At CV_h=5%, CV_k=25% or vise versa, the last term in Equation (4) changes DU_{lq} by less than 0.1%. Table 2 shows parts of Table 1 broken down for direct comparison. It appears that part of the discrepancy results from the variations in the simulation runs as evidenced by the differences in DU_S. Note that column 7 of Table 2 (column 10 of Table 1) gives the standard deviation of the simulation mean. Thus the true mean of DU_S will be within ±2 S_{DU} of the value given with a 95% level of confidence. Thus any differences in CV_D from simulation and from Equation (4) with or without the last term cannot really be

distinguished. Thus with the range of conditions given here, CV_D can be predicted with sufficient accuracy. As in the previous study (Clemmens, 1985), the value of S_{DU} (column 7) appears to be only affected by CV_k and not CV_h. Noting that k was chosen randomly and h^a was not, it appears that the variation in DU_{lq} from the expected value is caused by only the random components. Trends in parameters will change the expected value, but will probably not affect S_{DU}.

Table 2 also indicates some significant differences in DU_A depending upon whether the nonuniformity is caused by one source or the other. Clearly, the hydraulic distribution has more of a negative impact on uniformity when viewed in terms of CV. The magnitude of CV values for actual field conditions has not been adequately studied. For basins, CV_h values will generally be less than 15%. Values of CV_k for non-steady state infiltration under irrigation have not been reported in the literature.

Column 4 of Table 1 gives the back calculated DU_{lq}. Column 9 gives a comparison of the back calculated and actual DU_{lq}. From the magnitude of differences shown, it appears that the back calculating procedure is no better than the straight forward use of Equation (4). For CV_H <15% and CV_k <15%, neither procedure is off by more than ±2%. For any CV's shown, by using the average of DU_N and DU_{BC}, the error will be less than ±2%. It is interesting that for trickle pressure distributions, the back calculating procedure worked well and the DU_N values were conservative. Here, the procedure didn't work well and the DU_N values are generally nonconservative (ie, higher than actual). The main difference here is in the shape of the distributions. Pressure distributions have a high peak and then level off to a more uniform pressure (at least for horizontal lateral lines). Opportunity time distributions for basins have a large area with a relatively large, uniform depth and then drop off to a low point at the end of the field. Thus pressure distributions have a nearly constant pressure over the low quarter, while opportunity time distributions have rapidly changing values over the low quarter.

So far these analyses have been made only for simple, limited conditions. Since the shape of the distributions has a marked effect on the effects of combining these distributions, additional studies will have to be made to determine the impact of distribution shape under a wider range of conditions.

SUMMARY:

Two of the major factors which affect the distribution of water in surface irrigation systems are the opportunity time variations and soil spatial variations. Simple combinations of variance techniques can be used to determine the effective variance for these two factors, for coefficients of variation from 0 to 25%. However, since the shape of the distribution is unknown, estimates of distribution uniformity made from an assumed normal distribution will be in error. A procedure developed for trickle irrigation uniformity for back calculating an effective hydraulic distribution (analogous to opportunity time distribution) was found to be relatively ineffective for the level basin examples presented. The difference is in the shape of the distributions. These

results were developed from a Monte Carlo simulation model for soil variability and a previously developed opportunity time model for level basins. It was assumed that these distributions were independent, which will require further verification. It was also assumed that no trends existed in infiltration variation. These results should also be verified for a wider range of infiltration and advance exponents. It was also speculated that the variation in CV and DU_{lq} from the expected value is affected only by the variance components which result from random variables.

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Table 1. Results of simulations of level basin low quarter distribution uniformity. For advance exponent h=0.6, infiltration exponent a=0.6, field length broken into 100 segments, and 100 simulation runs for a random normally distributed infiltration consant k. All values shown in percent.

CV_h (1)	CV_k (2)	DU_N (3)	DU_{BC} (4)	$\overline{DU_S}$ (5)	$\overline{DU_A}$ (6)	S_{DU} (7)	Columns (3)-(6) (8)	Columns (4)-(6) (9)	$S_{\overline{DU}}$ (10)
5	5	91.0	90.4	91.1	90.9	0.6	+0.1	-0.5	±0.1
	10	85.8	85.4	85.6	85.8	1.0	0.0	-0.4	±0.1
	15	79.9	79.6	79.8	80.1	1.4	-0.2	-0.5	±0.1
	20	73.8	73.6	73.6	74.4	2.2	-0.6	-0.8	±0.2
	25	67.6	67.4	67.5	68.0	2.6	-1.4	-0.6	±0.3
10	5	85.8	84.3	85.9	84.8	0.6	+1.0	-0.5	±0.1
	10	82.1	80.9	81.8	81.7	1.2	+0.4	-0.8	±0.1
	15	77.1	76.2	77.0	77.4	1.6	-0.3	-1.2	±0.2
	20	71.6	70.8	71.5	72.2	2.2	-0.6	-1.4	±0.2
	25	65.8	65.1	65.6	66.6	2.7	-0.8	-1.4	±0.3
15	5	79.9	77.5	80.0	77.9	0.6	+2.0	-0.4	±0.1
	10	77.1	74.9	76.9	75.9	1.2	+1.2	-1.0	±0.1
	15	73.1	71.2	72.8	73.0	1.7	+0.1	-1.8	±0.2
	20	68.2	66.6	68.4	69.2	2.1	-1.0	-2.6	±0.2
	25	63.0	61.6	62.6	64.1	2.7	-1.1	-2.5	±0.3
20	5	73.8	70.2	73.8	70.7	0.6	+3.1	-0.5	±0.1
	10	71.5	68.3	71.3	69.2	1.1	+2.3	-0.9	±0.1
	15	68.2	65.2	67.9	67.3	1.7	+0.9	-2.1	±0.2
	20	64.0	61.4	64.1	64.5	2.1	-0.5	-3.1	±0.2
	25	59.3	56.9	58.7	60.2	2.6	-0.9	-3.3	±0.3
25	5	67.6	63.0	67.6	63.4	0.6	+4.2	-0.4	±0.1
	10	65.8	61.4	65.5	67.3	1.1	+3.5	-0.9	±0.1
	15	63.0	58.9	67.6	60.9	1.7	+2.1	-2.0	±0.2
	20	59.3	55.6	59.2	58.7	2.1	+0.6	-3.1	±0.2
	25	55.1	51.7	54.3	55.4	2.4	-0.3	-3.7	±0.2

CV_h = coefficient of variation of opportunity time effects on depth
CV_k = coefficient of variation of infiltration variation on depth
DU_N = Expected value of DU_{lq} computed for an assumed normal distribution from Equations (2) and (4)
DU_{BC} = Expected value of DU_{lq} computed for back calculated CV_h from Equations (2) and (4)
$\overline{DU_S}$ = Average value of DU_{lq} computed from actual CV_D from simulation runs with Equation (2)
$\overline{DU_A}$ = Average value of DU_{lq} computed from depth distribution from simulation runs with Equation (1)
S_{DU} = Standard deviation of DU_A from 100 simulation runs
$S_{\overline{DU}}$ = Standard deviation of expected mean of DU_A distribution for simulation

Table 2. Comparison of the effects of simulation for CV_N from Equation (4) with and without the last term.

CV_h	CV_k	DU_N without	DU_N with	$\overline{DU}_S$	$\overline{DU}_A$	$S_{\overline{DU}}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)
.25	.20	59.3	58.8	59.2	58.7	±0.2
.20	.25	59.3	58.8	58.7	60.2	±0.2
.25	.15	63.0	62.7	62.6	60.9	±0.2
.15	.25	63.0	62.7	62.6	64.1	±0.3

TITLE: CANAL CAPACITIES FOR DEMAND UNDER SURFACE IRRIGATION

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION:

Some irrigation projects are built to supply water to farms that apply water with surface irrigation methods. Water is often distributed to farmers within the project through a network of canals. Canals are used because they can be constructed more inexpensively than other available methods and because local labor and materials can be used. The simplest method of distributing water in a canal network is to supply a continuous flow of water to each farmer. The farmer is then responsible for distributing this water over different parts of his farm. This continuous flow system is simple to operate since once flow into the canal system is set, it does not change. However, since plants use water at different rates over the growing season, a continuous flow system would supply too much water early in the season and perhaps not enough water later in the season. Where available water is in short supply, this type of inefficiency is not reasonable. Some continuous flow systems adjust the supply flow rate periodically to try to more closely match plant water needs.

For surface irrigation, it is not practical to supply water at the rate at which the plants need water. For example, plants may use water at a rate of 2 to 10 mm per day, whereas surface irrigation systems generally are designed to apply from 50 to 150 mm, which will generally be applied in a period of 1 to 24 hours. This is dictated by soil water holding capacities, root zone depths, soil infiltration rates, and efficient irrigation stream sizes. Thus to achieve even a reasonable efficiency, an available irrigation stream must be rotated between different areas of land. If a farmer's land area is large enough, he may be able to handle a continuous flow, otherwise it is more practical to rotate the available irrigation stream among neighboring farmers. Operation of the canal distribution system for a rotation system does not change from that of a continuous flow system except for where water is actually turned into the farms. Rotation systems may also be inefficient if inflows are not adjusted through the season to match plant water requirements.

If the same stream that was once split among 8 farmers, for example, is now given to one farmer one day out of 8 days, his farm canals and the structure which turns water out of the project canal must be able to handle 8 times the flow rate. However, the canal which brings water to these 8 farmers has not changed in size. Now if efficiencies have been improved, the farm canal size could be reduced somewhat from the 8-fold increase. In addition, this increase in efficiency could potentially reduce the size of the supply canal. Thus here we see that if a change in delivery method can improve efficiency, while it may require larger canals on the farm, it may result in smaller project canals or more project area being serviced.

Surface irrigation systems are generally designed to be efficient within a small range of application depths. Since plants' water use rates vary widely over the season, the period between irrigations should also

change. Thus variations in frequency rather than flow rate are necessary to adjust a rotation schedule to match plant needs for surface irrigation. An adjustable frequency rotation system is somewhat difficult to develop. In addition, due to variations in soil characteristics and differences in crop selections, different fields within a rotation unit will actually need different rotation intervals during the same part of the season, a nearly impossible task for a rotation scheme.

It has been known for several decades that in order to be efficient in water use and productive in yields, a delivery system that is flexible in rate, frequency and duration is required. An extreme case of this flexibility is a demand system where any quantity of water is delivered whenever desired for any duration desired. Obviously such systems must operate within some practical bounds, eg. within a range of flow rates and within an overall seasonal water allocation. Returning to our eight farmers in rotation, if all eight wanted water at the same time, the supply canal to those eight farmers would have to be eight times as large as for a rotation. If each farmer wanted double the usual flow, say for half the duration, the canal would have to be 16 times as large. One alternative is to use farm reservoirs to accept water given in rotation, and apply it when needed. Another alternative is for farmers to arrange water deliveries in an effort to reduce the amount of overlap in demand. Of course the probability that all eight farmers would want water at the same time would be fairly low.

But how large a canal is necessary for a demand system, for example, if you want to be able to supply demand say 70 or 80% of the time? How is this overlap in demand mitigated by arranged schedules? And what should canal capacities be under these circumstances? This paper will attempt to quantify these issues and answer these questions.

Canal Capacity Relationships:

Canal capacities are based on the peak water use period and on the land area which they service. The peak water use rate, W_u, is defined as the peak consumptive use divided by the irrigation efficiency. It represents the amount of water to be delivered. Now, given a delivery flow rate Q_d which is established as an average (or maximum) for design of farm turnouts, the area that can be serviced by a continuous flow system would be

$$A_t = Q_d/W_u \tag{1}$$

with appropriate units conversion. This is also the area serviced by a single rotation of a rotation system, which approximately corresponds to the definition of a tertiary unit (Bos, 1979). Now if we are given a farm size or quarternary unit size which is serviced by one turn in the rotation, A_q, and rotation frequency, F, such that $N_r = 1/F$ farmers take turns in rotation, then the necessary delivery flow rate is

$$Q_d = A_q\, N_r\, W_u = \frac{A_q\, W_u}{F} \tag{2}$$

Of course, $A_t = A_q\, N_r$, or $A_t = A_q/F$.

It is useful to define these variables in relative terms. The flow rate of a canal, Q, is referenced to the turnout design flow rate, Q_d, to give a relative flow rate

$$Q_n = Q/Q_d \tag{3}$$

Similarly, the size of a canal service area, A, is referenced to both the farm or quaternary unit size, A_q, and the rotation or tertiary unit size, A_t, to give relative service areas

$$A_f = A/A_q \tag{4}$$

$$A_n = A/A_t \tag{5}$$

From Equations (1), (3), and (5) for a rotation or continuous flow system, we get

$$A_n = Q_n \tag{6}$$

Thus A_n and Q_n are convenient for analyzing the changes in canal capacity required for flexible (arranged and demand) delivery over that for the rigid (continuous flow or rotation) delivery schemes.

Clement's Demand Formulas:

Clement (1955) has developed two formulas for analyzing the demand requirements for irrigation. These formulas were developed for an irrigation project which used primarily sprinkler irrigation. Thus a particular field delivery point or quaternary unit has flow either on or off for a given day. Given that there are R delivery points, the first demand formula is used to find the number of users N such that the probability of N or fewer users will be using the system simultaneously is greater than some desired probability P_q. This is a supplier oriented view since it considers a time frequency of meeting capacity. The second demand formula finds the system capacity N such that the probability of the user finding the system at capacity or busy when he wants water (congestion) is less than some desired probability, P_a. This is a more user oriented view since it considers a use or demand frequency of over capacity. Clement's first demand formula is

$$N = Rp + U\sqrt{Rpq} \tag{7}$$

where N and R are defined above p is the frequency of irrigation, $q = 1-p$ and U is defined from $P_q = \pi(U)$ where the function π is the normal cumulative distribution function. This equation was derived by initially assuming that the probability of a particular farm unit being operated during a given day is described by a binomial probability distribution. A binomial distribution assumes that the probability of irrigating a given field on any particular day is independent of the past history of irrigations. This says that an irrigation would be just as likely today if we irrigated yesterday or a week ago. This does not seem reasonable for surface irrigation. Next, it was assumed that if R was large, that the binomial distribution could be approximated with a normal distribution. This approximation is valid only for large R. This formula supplies continuous values of N while in general, capaci-

ties are usually discrete multiples of the delivery rate. Clement's second demand formula is given by

$$N = Rp + U'\sqrt{Rpq} \tag{8}$$

where U' is found from

$$P_a \sqrt{Rpq} = \frac{\psi(u')}{\pi(u')} \tag{9}$$

where $\psi(U')$ is the normal probability density function. Some values for $\psi(U')/\pi(U')$ are given in Table 1. This formula was derived from a binomial distribution as a Poisson pure birth/death process. Again for large R, the binomial was replaced with a normal distribution. Clement recommends the first formula for $R < 100$ and the second for $R > 100$. It is also noted that no accounting is made for the condition where when demand is greater than capacity this excess demand must be handled in later periods. Clement recommends that the second formula (Equations 8 and 9) be used with $P_a = 0.01$. This also applies to the first formula and the P_q must be very high, say 0.99.

Clement's formulas can be written in the terminology of the previous section since by definition $R = A_f = A_n/F$, $N = Q_n$, $p = F$, $q = 1-F$, where Clement's terms are stated to the left of the equal sign. Equation (7), (8) and (9) become

$$Q_n = A_n + U\sqrt{A_n(1-F)} \tag{10}$$

$$Q_n = A_n + U'\sqrt{A_n(1-F)} \tag{11}$$

$$P_a \sqrt{A_n(1-F)} = \frac{\psi(U')}{\pi(U')} \tag{12}$$

Thus the second term in Equations (10) and (11) represent the excess capacity needed for demand.

Example:

Given a canal which services 2000 ha, with 10 ha per farm turnout, an irrigation frequency of 1 day in 12 days and a farm turnout capacity of 200 l/s, what is the canal capacity required for continuous flow and for demand from Clement's two formula with $P_q = 0.99$ and $P_a = 0.01$?

Given: $A = 2000\text{ha}$, $A_q = 10$ ha, $F = 1/12$, $Q_d = 200$ l/s

Calculate: $A_f = A/A_q = 200$, $A_n = A_f F = 16.67$

Solution: For a continuous flow $Q_n = A_n = 16.67$ from Equation (6) thus from Equation (3)

$$Q = Q_n Q_d = 200 \text{ l/s} \cdot 16.67 = \underline{3{,}333 \text{ l/s}}$$

For Clement's first demand formula

$P_q = 0.99 = \pi(u)$. From the normal cumulative distribution tables, $U = 2.324$. From Equation (10)

$$Q_n = A_n + U\sqrt{A_n(1-F)} = 1.667 + 2.324\sqrt{16.67(1-0.083)}$$

$$= 25.75$$

$$Q = 200\ \text{l/s}\cdot 25.75 = \underline{5{,}151\ \text{l/s}}$$

For Clement's second demand formula

$$\frac{\psi(u')}{\pi(u')} = P_a\sqrt{A_n(1-F)} = 0.01(3.909) = (0.0391)$$

this gives $U' \simeq 2.16$ from Table 1.

$$Q_n = A_n + U'\sqrt{A_n(1-F)} = 16.67 + 2.16\sqrt{16.67(1-0.083)}$$

$$= 25.11$$

$$Q = 200\ \text{l/s}\cdot 25.11 = \underline{5{,}023\ \text{l/s}}$$

It is clear that this high level of system performance (ie., less than 1% chance of not getting flow when desired) and flexibility has caused a large increase in the canal size. However, the change in efficiency that would often take place has not been considered.

The binomial (and then assumed normal) distribution used in the development of these formula which were derived for sprinkler irrigation do not appear to be appropriate for surface irrigation. Also, Clement's formulas are meant to apply only for relatively large scale systems (A_f > 100) and for large performance measures (congestion of 1%). However, lesser performance may be more appropriate for surface irrigation systems, particularly where arranged schedules are used. A simulation model was developed to simulate the demand for water under surface irrigation in order to test Clement's formula and to determine what actual demand capacities are needed.

Surface Irrigation Demand Simulation:

Irrigation dates and amounts were determined by simulation for 60 fields for 20 years with a modified version of the CREAMS model (Reinink 1985). Weather data for the 20 year simulation was developed with program WGEN (Weather Generator) based on the climate at Phoenix, Arizona. An arid climate was chosen because it is more typical of areas which are water short and in need of conservation measures. The 60 fields consisted of combinations of 4 crops as shown in Table 2. Five soils with varying water holding capacities as shown in Table 3 and 3 depletion levels, namely 45, 55 and 65% of available water, at which irrigation was initiated. CREAMS uses daily values of water use so that only the day of irrigation and the depth to refill the root zone is given as output. The crops were chosen to give a wide variety of consumptive use patterns and still be typical of crops grown in the area. The input to CREAMS (rooting depths and leaf area index) was adjusted to give consumptive

use values in agreement with those published by Erie et al. (1981), see Table 2 and Figure 1. Soils were chosen to represent a variety of water holding capacities (Table 3). A separate simulation model was developed to analyze the combinations of irrigations on dates during the peak use period of June, July and August (Julian Days 152 to 243). The average depth applied per irrigation was 113 mm (4.45 inch) with a standard deviation of 42 mm (1.65 inch). No adjustment was made for efficiency since only relative numbers are of significance. The average interval between irrigations was 16.3 days (F = 0.061), the standard deviation of average interval for the sites of 10.7 days. For the 60 sites, there was an average of 3.43 irrigations per day or 6311 irrigations over the 92 day interval for 20 years.

The fields were taken in groups of two, three, four etc., up to 60 in numbers by which 60 is evenly divisible in order to simulate canals with different downstream service areas. This was done day by day over the 1840 total days. The order (and thus groupings) of fields was chosen randomly. Two sets of output statistics were collected. The first was based on spreading the total demand for the canal over the 24 hour period, thus depth applied would have a significant influence. The second was based strictly on the number of fields being irrigated on a particular day. The statistics collected included the time based frequency of demand at a series of capacities and the demand based frequency at the same series of capacities. From this, the capacity representing a particular value of cumulative frequency could be determined for comparison with Clement's formula.

Many of the conditions represented by this simulation may be slightly unrealistic in that they do not represent an actual location. However, they may be viewed as a worst case situation since the variations in conditions is more than usual. On the other hand, farmer timing of irrigations would likely vary from that assumed here and thus more overlap could occur.

The nature of demand is influenced by specific site conditions. If capacities are based on supplying water for 24 hour periods, 7 days a week and irrigators will only work daylight hours, 5 days a week, the canals will probably not be capable of meeting the demand. More serious is the problem of controlling a canal system under this form of demand, but this is beyond the scope of this paper. Such practical considerations, however, make arranged delivery schedules more practical for surface irrigation than demand schedules.

RESULTS:

The results of the simulation model for a time based service frequency of 80% is shown in Figure 2. The simulation model with variations in applied depth and Clement's first formula are in very close agreement over the full range of values. This indicates that the assumptions used to develop this formula are reasonable even for surface irrigation. However, there is some question about the relevance of this formula as a service measure. Note that below a relative service area of approximately $A_n \approx 0.45$, the relative canal capacity drops below one. In fact, since the smaller canals are idle more than 80% of the time, their capacity goes to zero. This formula (and service measure) were probably

never intended for such small service areas (eg, A_n <1). A procedure was developed to adjust the frequency of canal demand being less than or equal to some value for canals which would be expected to be idle even under a rotation system (ie, A_n <1). A relative frequency, P_r, is found by adjusting the simulation time-based frequency, P_q, by the amount of expected busy time, A_n, with

$$A_n = \frac{1-P_q}{1-P_r} \tag{13}$$

Now the time-based frequency is found relative to the expected busy time rather than total time. These results are also shown in Figure 2. This form of time based frequency is more user oriented as shown by the increased capacity. This new frequency can be computed from Clement's first formula. Suppose in our previous example, A = 600 ha or A_n = 0.5 with F = 1/12 and, P_q = 80% and U = 0.84. This would give Q_n = 1.069. From Equation (13), solving for P_r

$$P_r = 1 - \frac{1-P_4}{A_n} = 1 - \frac{1-0.80}{0.5} = 0.60$$

Thus the computed capacity of Q_n = 1.069 will be adequate only 60% of the time that the canal is expected to be in service. This adjustment procedure is only valid for A_n < 1. It is not a very convenient procedure since P_r is found after the fact rather than being input.

The simulation model results for discrete demand are also shown in Figure 2, where only the number of fields being irrigated is of concern. Note that the line for continuous variations in demand falls through the middle of the stair stepping pattern. Also shown in Figure 2 are the adjusted simulation results for P_q = 95% along with Clement's first formula over part of the range for comparison. Agreement is not as good here as it was at P_q = 80%.

The results of the simulation for a demand-based service frequency are shown in Figure 3 along with Clement's second formula. The capacities from the simulation model at an 80% service level are significantly higher than Clement's formula. This is not too surprising since Clement's formula does not consider any variations in quantity or depth delivered to each user. This variation can be removed from the results if the distribution of depths is known. A cumulative probability of 80% for this distribution occurs at 147.3 mm (5.8 inch). Thus the capacity for a uniform application (and the same timing distribution) would be in direct proportion to the mean or 113/147.3*100 = 76.7% of the simulation output. These values are plotted in Figure 3 and show much better agreement with Clement's formula, particularly at high A_n values. The stair stepping pattern for discrete demand is to the left of Clement's formula, again indicating the effect of variations in demand quantity. Note also that capacities for Clement's formula drop below unity, while for the simulation they do not.

A comparison of the demand-based results of the simulation and Clement's formula for demand service levels of 50, 80, 90 and 95 percent are shown

in Figure 4. The results are considerably different from Clement's second formula throughout the entire range.

DISCUSSION:

It was noted earlier that all the simulation results lie above $Q_n = 1$ while Clement's formulas have $Q_n < 1$. A relative canal capacity of 1 would normally be used with a rotation system. In fact, for a strict rotation system, canal capacities would be in discrete increments of the delivery rate, Q_d, or would be integer values of Q_n. Thus, rather than the straight line (ie. $Q_n = A_n$) of a continuous flow system, a strict rotation system would have a stair stepping pattern. In this case as A_n approaches zero, Q_n approaches one. This pattern is shown in all the simulation results, even though this was not stipulated as a requirement. This makes sense since even the smallest area to which water is delivered should receive the design delivery rate. For Clement's formulae, Q_n approaches zero as A_n approaches zero. Thus Clement's formulae are not appropriate below $A_n = 1$. However, is it appropriate to design canals in noninteger multiples of Q_d for arranged and demand delivery systems? If the delivery flow rate is fixed by policy, then it is not appropriate. However, if flexibility in flow rate is allowed, then it makes sense since the farmers can order a flow rate which is efficient for the current conditions. In some cases it may be above Q_d, and in others it may be below Q_d so that flow in the canal can be split.

It should be emphasized that arranged and demand schedules can often result in higher farm irrigation efficiencies. This of course depends upon the capabilities of the farmers. Increasing flexibility can make canal operations more difficult resulting in lower conveyance efficiencies caused by the inability to uniformly distribute water. Automatic controls can greatly reduce this problem. Without automatic controls, conveyance losses due to regulation (not seepage) for non-automated canal systems with arranged schedules are on the order of 10-15%. This is generally as good as water is distributed in most rotation systems. In general, the increase in efficiency on farm will offset the increase in relative canal capacity. The tendency is for larger delivery rates, larger quaternary canals, slightly larger tertiary canals and smaller main canals when comparing flexible (arranged) to rigid (rotation) schedules. This analysis has ignored the fact that when congestion occurs, those waiting for service potentially can cause more congestion in later periods. Thus the actual congestion is higher. We can assume that by selecting a capacity with a simple probability of 1% congestion, increased congestion by this 1% will be negligible. However, for a capacity at a simple probability of 50%, increased congestion is certain to be significant and the actual congestion higher than 50%. This makes the true capacity required for 50% demand service higher than indicated here, thus bringing these capacity curves farther apart. The magnitude of this shift in capacity has not been evaluated here.

Arranged schedules are used to reduce the capacity requirements of a demand schedule and to allow supply oriented operation of canals. Arranged schedules are a combination of supply and demand oriented systems. Different arrangement schemes allow different types and degrees of flexibility. Earlier, the time based service capacities were adjusted to account for canal non-use periods, a more demand oriented

approach. Also, demand capacities were reduced by removing the fluctuations in quantities ordered, a more supply oriented approach. The results of these two approaches is shown in Figure 5 for 80 and 95% service measures. These two approaches are in reasonably close agreement on required canal capacity, being different mixtures of supply and demand orientation. Thus it may be reasonable to use these capacities for arranged delivery systems.

It is difficult to judge what level of performance is necessary for the efficient operation of a canal system. It may be useful to compare these results with the actual capacities of existing irrigation projects with flexible delivery schedules. Figure 6 shows data from two different canal systems; the Salt River Project (SRP) in central Arizona and the Wellton-Mowhawk Irrigation and Drainage District (W-M) in southwestern Arizona. Data for SRP was taken from laterals off the Eastern Canal for 1978 acreages (Clemmens, 1974). The high relative capacities are partially due to land which has been taken out of production by urban growth. However, SRP capacities are still significantly higher than W-M capacities. SRP operates on a more flexible schedule than W-M with 1 day rather than 3 day lead times and fewer conflicts in arrangement. However, with 3 day lead times, delivery within ± 1 day can allow arrangements to reduce peak demand. This is not meant to imply that arranged schedules require long lead times. The arranged and demand curves shown represent the simulation results for 90% service level for the adjusted (with depth variations removed) and original capacities. Capacities for 80 and 95% service levels are only slightly different. The Wellton Mohawk Irrigation and Drainage District appears to have been designed with an equation of the form $Q = 30 + 0.01875A$ as a guide (Slocum, 1980). When translated to the notation used here, with Q_d = 425 l/s (15 ft^3/s), W_u = 11.33 mm/day (0.446 inch/day), and A_t = 324 ha (800 ac) this equation becomes $Q_n = A_n + 2$. This equation is shown in Figure 6 along with some actual values for canals in the project. It appears that the equation was used only for the larger canals (say $A_n >$ 1.5) and probably rightfully so since the equation gave increasingly better service for very small A_n. It appears that actual capacities for small service areas may have been a little low, or at least representing lower service capabilities than the larger canals. Capacity problems have arisen for canals with small service areas. Even so, this project operates very efficiently on an arranged schedule with flexibility in rate, frequency and duration.

The arranged and demand curves at a 90% service level are shown in Figure 7. Note that the arranged schedule only requires a small increase in canal capacities over the rotation and continuous flow schedules. These differences may easily be overcome by increases in efficiency for most lateral and main canals. A demand system, however, requires considerably greater capacities being 2 to 3 times (for $A_n >$ 2) greater than that required for continuous flow. It is doubtful that the flexibility offered could alone improve efficiencies that much. Thus arranged systems can be justified by reductions in system costs and improved operations, while expanding canals to handle demand may not be easily justified. Farm reservoirs provide an attractive alternative when demand operation is required. Also shown in Figure 7 are the design curve for W-M and the results of Clement's second formula (Clement II) for $P_a = 0.10$ and $F = 1/16.3$. Note that Clement II falls

between the demand and arranged demand. The exact location of the arranged curve is subject to some speculation and may depend on a number of operational factors, thus this formula could be used for arranged schedules. However, it is fairly certain that Clement's formula is not reasonable for the type of demand used in this simulation. The variations in depth and frequency for this simulation were chosen to give extreme conditions; however, frequency was essentially random whereas in actual practice external circumstances may cause more overlap in demand. Thus the demand curve shown is reasonable. Clement II is reasonably good at this service level from $0.2 < A_n < 2$, with values 10 to 15% higher than the arranged curve for $A_n > 2$. The W-M design curve is relatively good for $A_n > 2$. For $A_n < 2$ it gives overly conservative results. The arranged curve can be approximated for simplicity by the following

$$\begin{aligned} Q_n &= 1.6\ A_n + 1 && \text{for } A_n \leq 1 \\ &= A_n + 1.6 && \text{for } A_n \geq 1 \end{aligned}$$

Note that this is very similar in form to the W-M equation, at least for $A_n > 1$. The demand curve can be approximated by

$$\begin{aligned} Q_n &= 4\ A_n + 1 && \text{for } A_n \leq 1 \\ Q_n &= 1.5\ A_n + 3.5 && \text{for } A_n \geq 1 \end{aligned}$$

which is also of a similar form.

SUMMARY:

A simulation model was used to determine canal capacities for demand and arranged irrigation distribution systems for surface irrigation. Simulation results were compared with Clement's two demand formulae developed for sprinkler irrigation supply systems in France. For comparison, canal capacity, Q_n, is expressed as a multiple (fraction) of the design farm delivery rate and service area, A_n, is expressed as a multiple (fraction) of the area for which the design farm delivery rate could meet the daily water requirements if delivered on a continuous basis (ie., rotation area). The simulation model developed irrigation frequencies and quantities for 60 sites representing a wide range of crops, soils, and irrigation management strategies over a 20 year period with water use and depletions for a simulated arid climate.

It was found that for surface irrigation demand systems, Clement's formulae under predicted the necessary capacities. Clement's first formula is particularly poor for $A_n < 1$ (less than 1 rotation area) since the canal capacity is allowed to go below the farm delivery rate ($Q_n < 1$).

Capacities for arranged systems were determined by adjusting supply oriented capacities to reflect relative service time (more demand oriented) and by adjusting demand oriented capacities to remove quantity variations (more supply oriented). This is reasonable since arranged schedules are a mixture of supply and demand oriented considerations. These results were compared with capacities of existing arranged canal systems. Clement's formulae are in reasonable agreement with the arranged canal capacity curve, being generally 10-15% higher.

Finally simple canal capacity equations were developed for both demand and arranged schedules which are easy to use. These equations are in a form similar to those used in the design of an existing irrigation project.

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Table 1. Values of $\psi(U')/\pi(U')$ and $\pi(U)$ for use in Clement's demand formulas where $\psi(U')$ is the normal probability density function and $\pi(U)$ is the cumulative normal distribution function.

U or U'	$\psi(U')/\pi(U')$	$\pi(U)$
0.0	0.798	0.500
0.1	0.735	0.540
0.2	0.635	0.579
0.3	0.617	0.618
0.4	0.562	0.655
0.5	0.509	0.692
0.6	0.459	0.726
0.7	0.412	0.758
0.8	0.367	0.788
0.9	0.326	0.816
1.0	0.287	0.841
1.1	0.252	0.864
1.2	0.219	0.885
1.3	0.190	0.903
1.4	0.163	0.919
1.5	0.139	0.933
1.6	0.117	0.945
1.7	0.0984	0.955
1.8	0.0819	0.964
1.9	0.0675	0.971
2.0	0.0553	0.977
2.1	0.0448	0.982
2.2	0.0360	0.986
2.3	0.0286	0.989
2.4	0.0226	0.992
2.5	0.0176	0.994
2.6	0.0137	0.995
2.7	0.0104	0.996
2.8	0.0079	0.997
2.9	0.0060	0.998
3.0	0.0044	0.999
3.1	0.0033	0.999
3.2	0.0024	0.999
3.3	0.0017	0.999
3.4	0.0012	1.000

Table 2. Crops used in CREAMS model with rooting depths as input and resulting consumptive use over 92 day period of June, July and August.

Crop	Effective Rooting Depth inch	m	Representative Consumptive Use of 92 day period inch	mm
Alfalfa	78	1.98	32.1	815
Cotton	60	1.52	26.1	663
Citrus	54	1.37	19.1	485
Sorghum (double cropped)	60	1.52	26.7	678

Table 3. Soils chosen and water holding capacities for input to CREAMS model.

Soil Type	Available water %	mm/m	in/ft
Loamy Sand	8.4	84	1.0
Sandy Loam	10.9	109	1.3
Very fine sandy loam	14.3	143	1.72
Loam	16.5	165	1.98
Silty clay loam	19.9	199	2.39

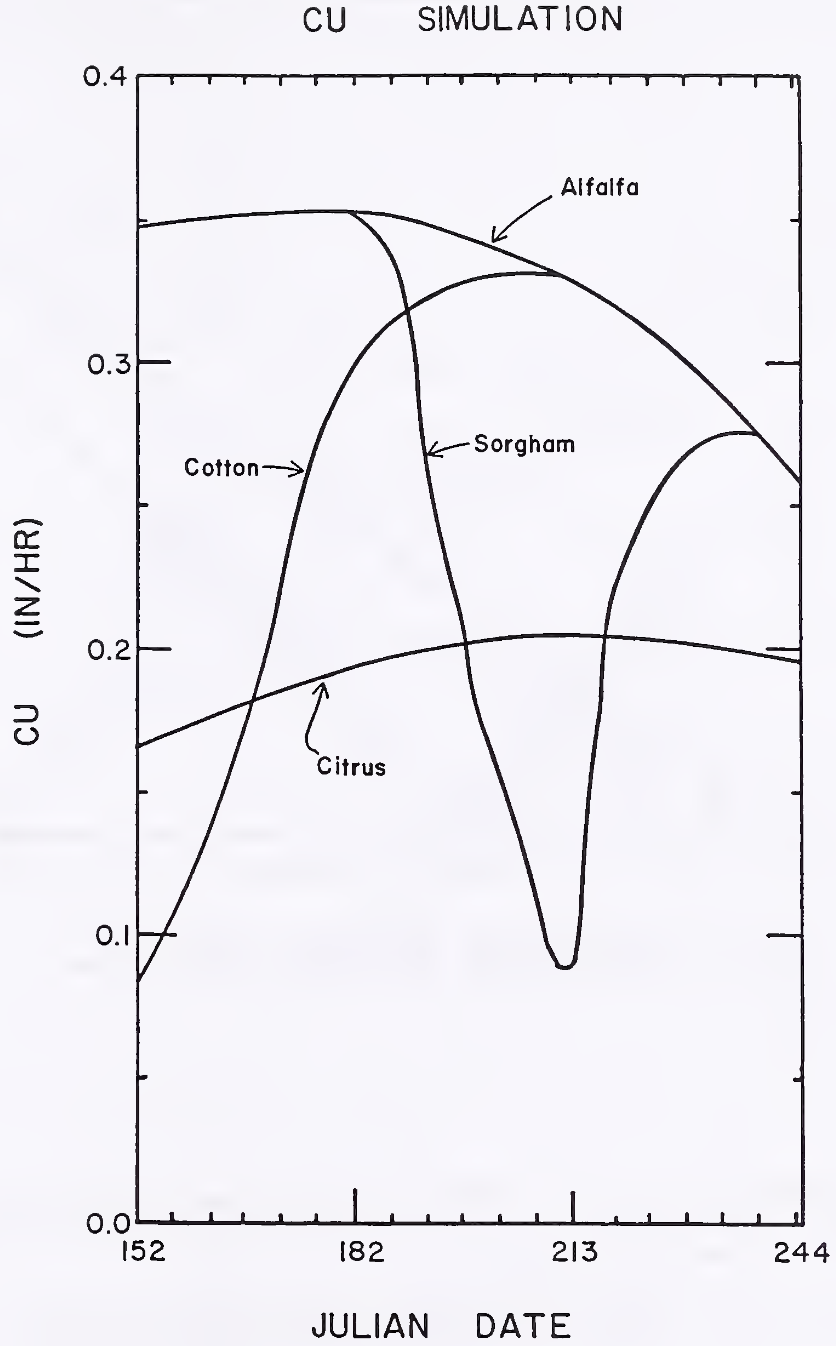

Figure 1. Representative consumptive use during peak use period of June, July and August (Julian days 152 to 243) for the four crops used in the simulation.

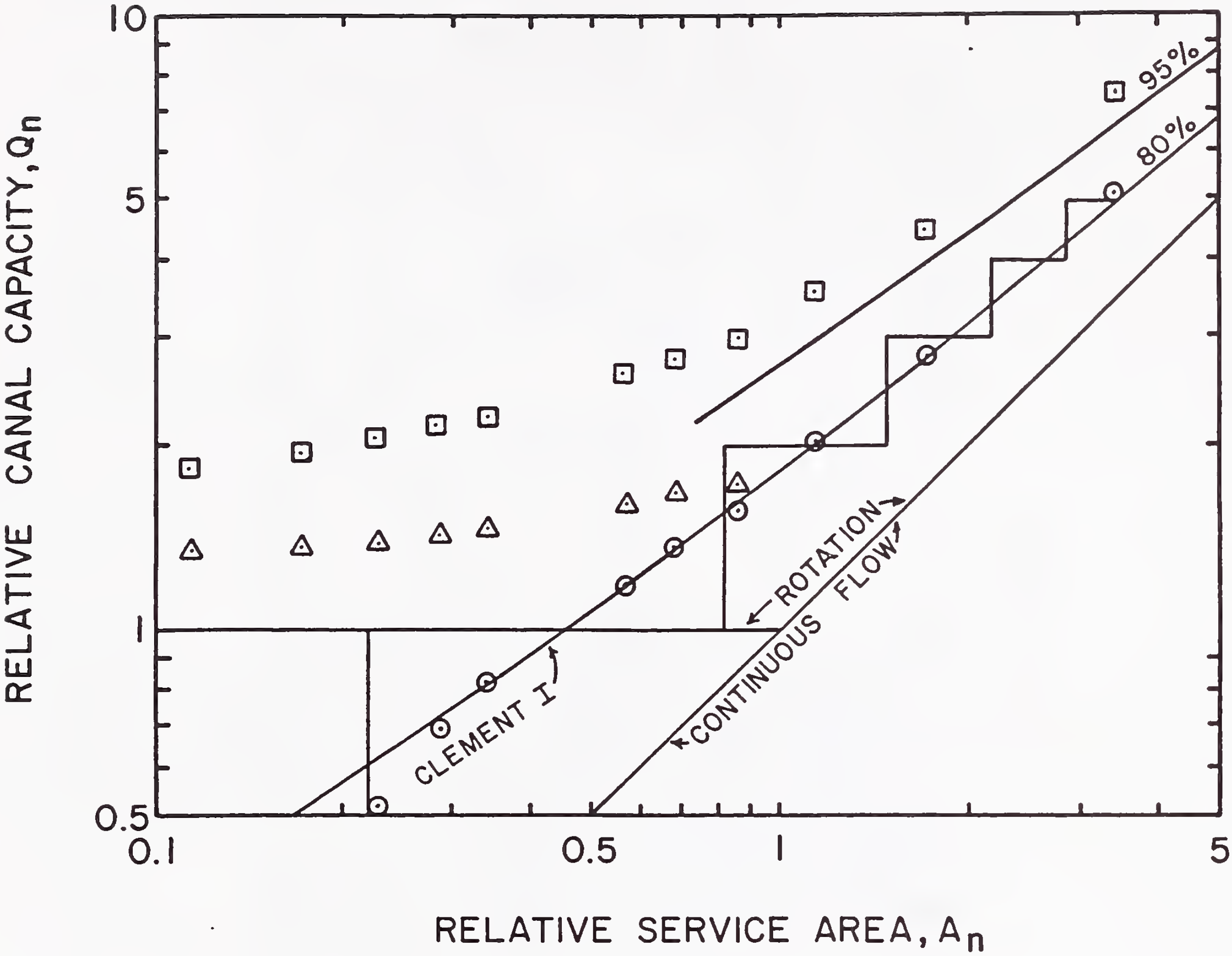

Figure 2. Comparison of canal capabilities for time (supply) based service levels of 80 and 95% from simulation and from Clement's first formula (Clement I).

O – simulation data for P_a = 80%

Δ – simulation data adjusted for idle time for P_a = 80%

[] – simulation data for P_a = 95% with data adjusted for $A_n < 1$.

DISCRETE – simulation results for integer increments of canal capacity

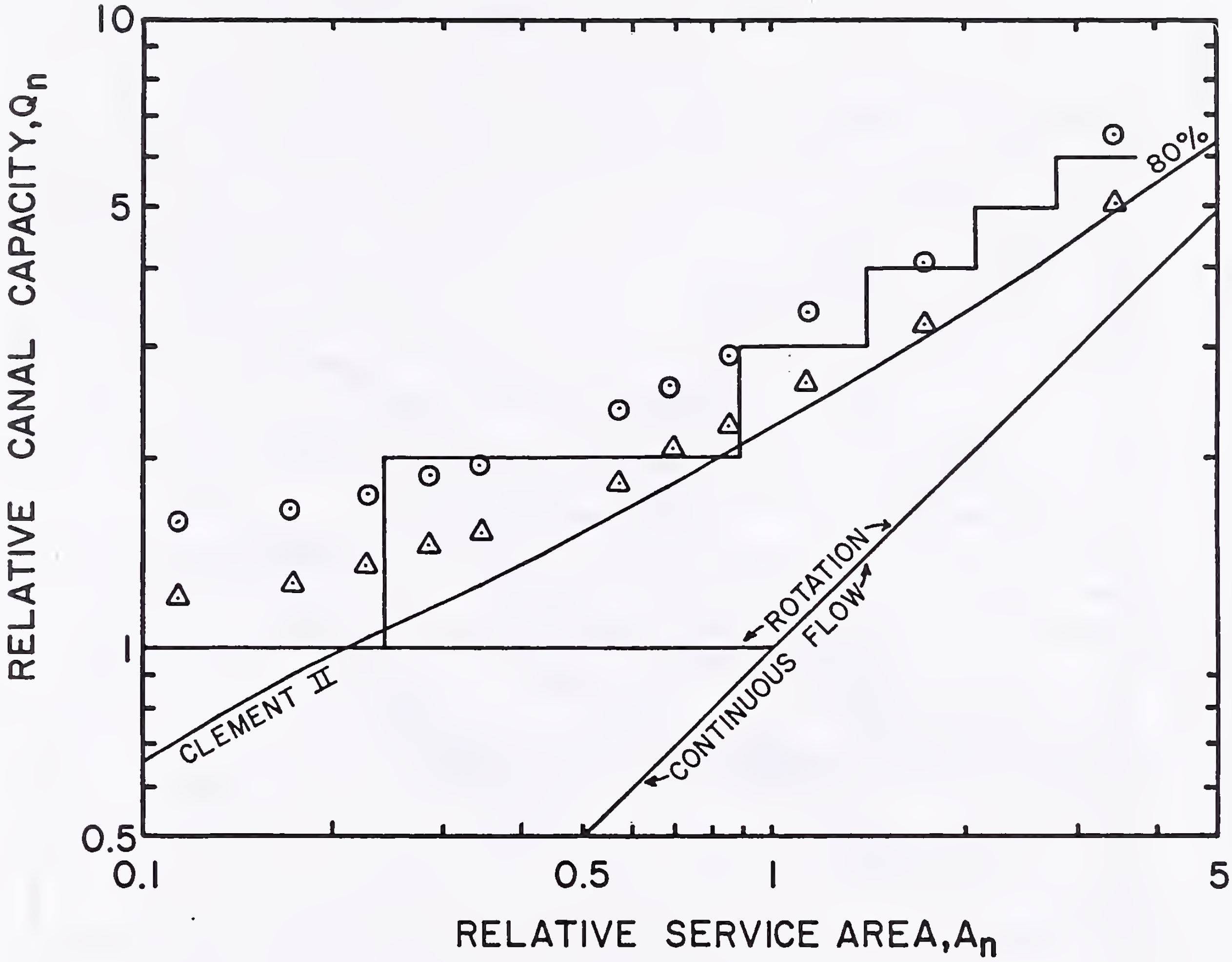

Figure 3. Comparison of canal capacities for demand based service level of 80% from simulation and from Clement's second formula (Clement II).

O – simulation data

Δ – simulation data adjusted to remove variations in quantity ordered.

DISCRETE – simulation results for integer increments of canal capacity

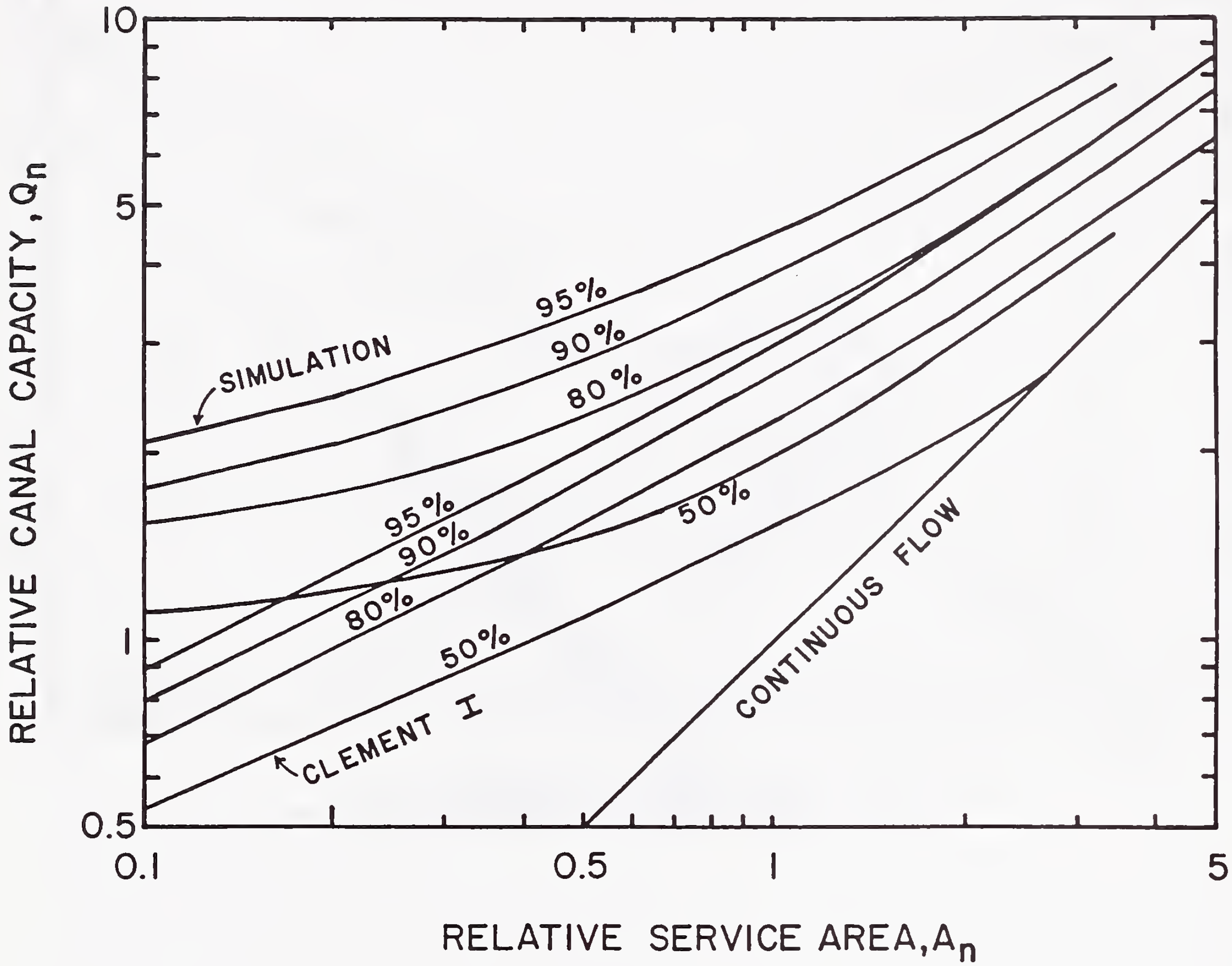

Figure 4. Comparison of canal capacities for demand based service levels of 50, 80, 90 and 95% from simulation and from Clement's second formula.

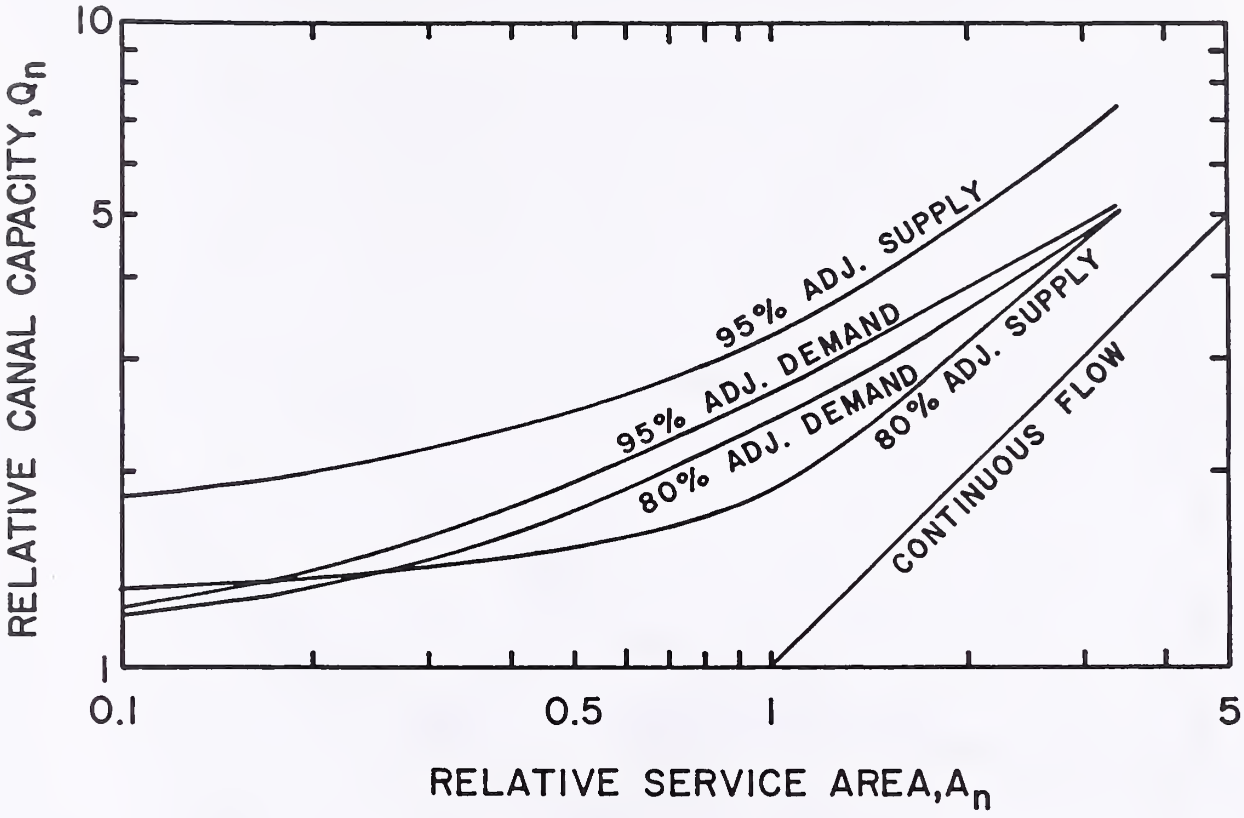

Figure 5. Canal capacities for service levels of 80 and 95% for supply based service levels adjusted for demand (ADJ SUPPLY) and for demand based service levels adjusted for supply (ADJ DEMAND) from simulation.

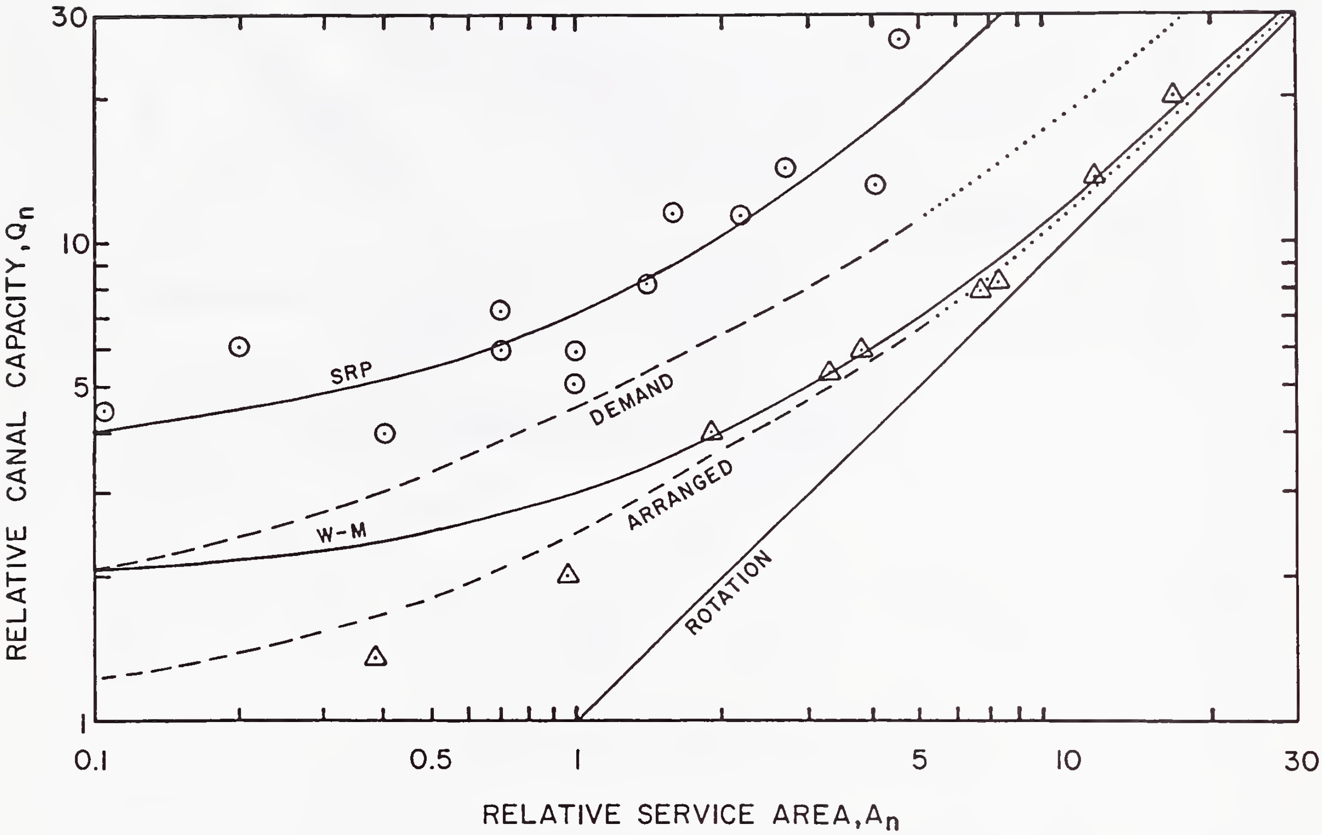

Figure 6. Canal capacities from actual irrigation projects compared to rotation, arranged and demand schedules, the latter two at 90% service levels.

O - sample data from the Salt River Project
SRP - curve approximately fitting Salt River Project data
Δ - sample data from Wellton-Mohawk Irrigation and Drainage District
W-M - design guide for Wellton-Mohawk Irrigation and Drainage District
DEMAND - simulation results for demand service level of 90%
ARRANGED - simulation results for adjusted demand service level of 90%

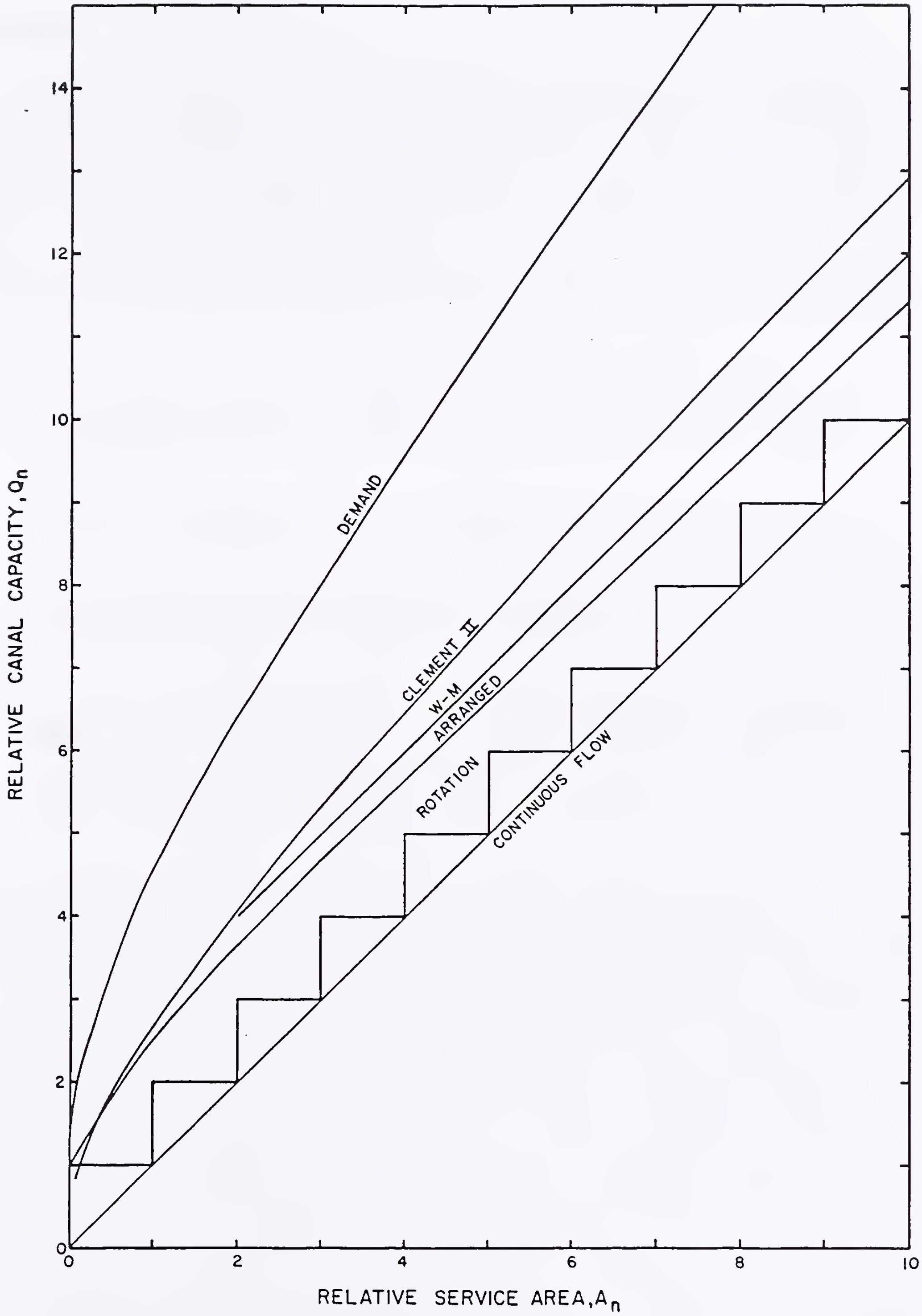

Figure 7. Canal capacity design relations.

TITLE: CANAL OPERATIONS

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION:

The operation of canal systems that deliver water for irrigation can have a significant impact on the farm operator's ability to apply water efficiently and uniformly. Irrigation delivery policies and conditions are usually established very early in the life of the project. Often, these policies and conditions limit the crops that can be considered and limit the effectiveness of modern on-farm irrigation systems that can significantly improve water management. Existing control schemes, structures, and canals for many delivery systems are not geared toward providing flexibility for farm operations. Some more specific problems follow:

1) Very little detailed information exists on the impact of district operations on farm deliveries and farm irrigation practices.

2) Current instrumentation for monitoring canal operations is either too costly or not accurate enough.

3) Canal capacity requirements for flexible irrigation delivery schemes have not been adequately studied.

4) Little has been written about the design of fixed structures in terms of their response to changes in incoming discharge. Existing control structures for maintaining a constant downstream head (or discharge) require electrical power (and are thus too expensive), cannot maintain accuracy to a reasonable level, or are not adjustable.

We are approaching the problem from a number of directions. First, it is viewed from the farm operators' standpoints, that is, what constraints does the delivery system put on his farm operations. This includes such things as delivery schedules, lead time for ordering, ability to change flow or duration during the delivery period, and the uniformity of delivery. The second view is taken from the district's standpoint, that is, how can I provide better service for the same cost. This includes analysis of operational procedures, control schemes, control structures, and canal capacities. A third approach represents an integration of these two views, that is, what will give the best overall results. The idea is to develop easy to manage district systems that can still provide the farmer with enough flexibility that his management is also simple. Objectives of our research effort are to improve water deliveries through: 1) a better understanding of the impact of delivery policies and operating conditions on farm operations, 2) a better understanding of canal operations and their effect on deliveries, and 3) the development of improved operational schemes and associated structures. Some specific research approaches follow.

1) A detailed study will be initiated to monitor the operation of individual lateral canals. We will monitor all inflows and

outflows plus water levels in the lateral. We will hopefully be able to study the effects of different operational policies and structures on canal transients and delivery uniformities.

2) We are attempting to develop and to encourage the commercial development of low cost, highly accurate instrumentation for measuring water levels in open channels. We will test any new schemes and available instruments to evaluate accuracy and cost effectiveness.

3) We will simulate the conditions of water demand under surface irrigation in order to determine a relationship between capacity and ability to deliver water on demand or as arranged for various levels within a canal system.

4) We will work on developing new gate control mechanisms for maintaining constant flow at an offtake from a canal or reservoir.

RESULTS AND CONCLUSIONS:

1) Canal operations monitoring - In 1984 contacts were made with two irrigation districts (Imperial Irrigation District, IID, and the Wellton-Mohawk Irrigation and Drainage District, WMIDD) for the purpose of developing a cooperative research program to study canal operations.

The IID has an ongoing conservation program in which we plan to participate. They are currently monitoring inflows and outflows from about 50 fields which are spread around the district. We planned on concentrating on four laterals that were chosen for initial study. They were chosen because of their location relation to check structures in the main canal and because two were completely lined and two were only partially lined. There are 130 delivery points on these four laterals. Of these delivery points, about 10 have previously installed flumes. The rest will need flume installations. An additional 9 or 10 flumes will have to be installed in district lateral canals. The WMIDD has also agreed to allow us to study canals within their district. We have chosen two canals for our initial study. These two have approximately 60 delivery sites, half of which have flumes already installed.

These two districts have some interesting differences. The IID has 500,000 ac, 3 days notice, deliveries in 24 hour increments, 11 cfs standard deliveries and 8 hour ditchrider shifts. The WMIDD has 60,000 ac, 3 days notice, deliveries for any duration, standard deliveries of 15 cfs (with 20 to 25 cfs more common) and ditchriders on 24 hour call. Of interest will be the differences in operation for these two districts.

2) Canal monitoring instrumentation - We surveyed a large portion of the commercially available flow monitoring equipment and found it far too costly (> $1000 per head). Generally the equipment is not simple to install, requires a stilling well in many instances, requires excessive power to operate by battery for extended periods, and does not meet our head-detection accuracy requirements (± .01 ft). The most economical approach presently available to adequately monitor a number of water levels in the same proximity appears to be a recently introduced data

logging system (Easy Logger by Omnidata) coupled with a bubbler/pressure transducer system developed at the U. S. Water Conservation Laboratory. Bartex, Inc., presently manufactures a water level sensing system, based on an acoustical (shock wave) transducer, that is simple to use in the field, exceeds our accuracy requirements, but in its present form is too costly. The company is interested in developing a unit that includes a single sensor/logger with simplified electronics mounted directly on the side of a concrete lined canal, without a stilling well. The expected marketing price of such a unit is $750 or less if the development, manufacturing and tooling costs were defrayed by the Government or other interested entity. The estimate for such a one-time development charge is 135-175 thousand dollars.

3) Canal capacities - A Frenchman named Clement developed two different equations for canal capacities for demand systems. His equations were developed for sprinkler irrigation where it was assumed that there was a known probability of a particular field being irrigated on a given day regardless of prior irrigations, and that all irrigations were of the same rate and duration. This is not too realistic for surface irrigation.

A simulation model was developed to determine canal capacities under surface irrigation. Time and amount of irrigation were simulated for 20 years on 60 fields to develop data to determine a distribution of canal capacities. These results were compared with Clement's equations and existing capacities in existing canal systems which operate under arranged schedules. The results were mixed. Clement's first equation did not predict the results well. His second equation was adequate within a certain range, but only when uniform rate and duration are assumed. At a given level of performance, variations in rate, duration and volume applied showed a need for much higher capacity. One of the difficulties of making a determination on canal capacity is in determining appropriate performance levels. This would require an analysis of the impacts of performance on farm operations which is yet to be done.

4) Gate controller - A gate controller mechanism was devised and tested, which will maintain a constant downstream discharge, which is powered only by the head upstream from the gate (no electricity), and which is continuously adjustable (any discharge can be set). A prototype system was set up in the hydraulics lab with a butterfly valve on a pipe supplying a short channel section. The upstream pressure was periodically changed to simulate changes in upstream water level. The system returned to equilibrium quickly (say $\leq$ 10 min.) and accurately (to within $\pm$ 1 mm), even for quick step changes in upstream head (changes in the field are gradual). A similar mechanism was installed at a test site at the Salt River Project (SRP). The site has an 8' wide radial gate at the entrance to a channel which has a flume. Flow is diverted from an upstream reservoir. Excess flow (in excess of what is set for the channel) flows over a Cipoletti weir into a bypass channel. Some initial testing was done in 1984. The system appears to control the downstream water level to within about ± 3mm (or ± 2% of flow). This system has the potential for regulating the outlet of a reservoir, in addition to farm or lateral offtakes from canals.

SUMMARY AND CONCLUSIONS:

A study has been initiated to monitor the operation of individual laterals in the Imperial Irrigation District and the Wellton Mohawk Irrigation and Drainage District. The specific laterals selected were chosen for their unique location within the district delivery system relative to main canal control structures. Initial surveys for instrumentation of all delivery points were completed.

To monitor a number of water levels in the same proximity, the most economical approach includes the use of a recently introduced data logging system from Omnidata coupled with a bubbler/pressure transducer system developed at the U.S. Water Conservation Laboratory. Plans are being made to evaluate the utility of this system for our canal monitoring program. We have worked closely with a number of companies in encouraging commercial development of low cost, highly accurate instrumentation for measuring water levels. Bartex, Inc. is interested in developing a unit that includes a single sensor/logger which mounts directly on the side of the concrete lined canal. The system would be easy to install in the field, would exceed our accuracy requirements, and would have an expected marketing price of $750 or less if development, manufacturing, and tooling costs were defrayed by the Government or other interested parties.

Some preliminary studies on the relationship between canal capacity and ability to deliver water on demand or as arranged were completed. A simulation model was developed to determine canal capacity requirements for surface irrigation.

A gate controller was devised and tested which will maintain a constant downstream water surface elevation. The controller is powered by the head upstream from the gate, hence requiring no electricity. The downstream head setting is adjustable. A prototype system was set up and tested in the laboratory and controlled the downstream water surface to within $\pm$ 1 mm when experiencing abrupt upstream head changes. A similar system was installed in cooperation with the Salt River Project where an eight foot wide radial gate at the entrance of a channel was controlled. The system appeared to control the downstream water surface to within $\pm$ 3 mm.

PERSONNEL:

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TITLE: FURROW INFILTRATION: VOLUME BALANCE EQUATIONS

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION:

The methods developed here apply to determining infiltration under furrow irrigation when the following information is collected for individual furrows: inflow hydrograph, outflow hydrograph, furrow cross-section, and flow depth hydrographs at a number of stations. The basic scheme is to compute a volume balance at discrete time intervals. At any given instant of time, the net volume of water that has entered the furrow (and not yet run off) must be known. The computations are broken into two parts. The first part is to compute the total volume of water on the surface. This volume is subtracted from the net volume which has entered the furrow, resulting in the volume infiltrated. The second part of the computations determines how the infiltrated water is distributed along the furrow and thus determines the infiltration function or equation constants.

SURFACE VOLUMES:

Many furrow shapes can be adequately described by a power function of the form

$$B = Cy^M \tag{1}$$

where y is the depth, B is the top width, and C and M are empirical constants. Not all furrows have a uniform cross-section with either time or distance, thus the constants C and M should be allowed to vary with either time or distance. Since surface volumes are computed at discrete times, changes in cross section can be accommodated by simply changing constances. However, since the volume between stations (where depth and cross-section are measured) must be determined, some means of determining intermediate values of cross sectional area must be found. The approach taken here is to allow the top width at a given depth to change linearly from one station to the next. This can be expressed by

$$\frac{B(y,x) - B(y,x_1)}{B(y,x_o) - B(y,x_1)} = \frac{x - x_1}{x_o - x_1} \tag{2}$$

where x_o and x_1 are the distances to stations 0 and 1 respectively, x is an intermediate location and B(y,x) is the top width at depth y and location x. Note that the constant C and M are defined only at x_o and x_1 and Equation (2) is solved for B(y,x).

Since the depth of water in the furrow changes with distance, a method for estimating the flow depth between stations must be used. Two methods are presented here. The first assumes a power function of depth with distance of the form

$$\frac{y - y_1}{y_o - y_1} = \frac{x - x_1}{x_o - x_1}^{\beta} \tag{3}$$

where y_o and y_1 are the depths at stations 0 and 1 respectively and β is the usual surface shape factor. (In actuality $y_1 = y_1(t)$, however Equation (3) implicitly assumes a constant known time). When β=1, the change in depth y with distance x is linear. When β=0, $y=y_o$ between x_o and x_1. The second method assume a power function of area with distance, where

$$\frac{A - A_1}{A_o - A_1} = \frac{x - x_1}{x_o - x_1}^{\alpha} \tag{4}$$

where A is the cross sectional flow area for a depth y, the subscripts o and 1 are as previously defined and α is the area shape factor. Two cases are considered for the development of general equations. The first case represents the tip cell of an advancing water front. The volume balance can only be determined at times when the tip cell reaches a known station. Defining this as station 1, we get y_1=0 with y_o a measured value and β is some positive value greater than zero (and generally less than one). For the other cells of an irrigation stream (second case) where y_1 and y_o are positive values, a linear depth (or area) profile is assumed wherein β=1 (or α=1). These surface volumes are derived from

$$V_s = \int_{x_o}^{x_1} \int_{o}^{y(x)} B(y,x)dy\ dx \tag{5}$$

Under the assumption of water depth as a function of distance and a uniform cross section between stations 0 and 1, the surface volume is for the tip cell

$$V_s = (x_1 - x_o) \frac{Cy_o^{M+1}}{M+1} \frac{1}{1 + \beta(M+1)} \qquad \text{for } \beta>0,\ y_1 = 0 \tag{6}$$

and for the intermediate cells

$$V_s = \frac{(x_1 - x_o)}{(Y_1 - Y_o)} \frac{C}{(M+1)(M+2)} (y_1^{M+2} - y_o^{M+2}) \qquad \text{for } \beta = 1 \tag{7}$$

A similar pair of equations for nonuniform cross sections gives for the tip cell

$$V_s = (x_1 - x_o) \left[\frac{C_1\ y_o^{M_1+1}}{(M_1+1)(1+\beta(M_1+1))} + \frac{C_o\ y_o^{M_o+1}}{(M_o+1)(2+\beta(M_o+1))} - \frac{C_1\ y_o^{M_1+1}}{(M_1+1)(2+\beta(M_1+1))} \right]$$

$$\text{for } \beta>0,\ y_1 = 0 \tag{8}$$

and for the intermediate cells

$$V_s = \frac{(x_1-x_0)}{(y_o-y_1)}\left\{\left[\frac{C_1 y^{M_1+2}}{(M_1+2)(M_1+1)} - \frac{C_1 y^{M_1+2}}{(y_o-y_1)}\left\{\frac{y}{M_1+3} - \frac{y_1}{M_1+2}\right\} + \frac{C_o y^{M_o+2}}{(y_o-y_1)(M_o+3)}\left\{\frac{y}{M_o+3} - \frac{y_1}{M_o+2}\right\}\right]\Bigg|_{y_1}^{y_o}\right\} \quad \text{for } \beta = 1 \tag{9}$$

Note that flow is from section 0 to section 1.

A similar set of equations can be developed from the assumption of flow area as a function of distance. For a uniform cross section we get for the tip cell

$$V_s = (x_1 - x_o)\,\frac{Cy_o^{M+1}}{M+1}\,\frac{1}{1+\alpha} \qquad \text{for } \alpha>0,\ y_1 = 0 \tag{10}$$

and for the intermediate cell

$$V_s = (x_1 - x_o)\,\frac{C}{M+1}\,\frac{1}{2}\,(y_1^{M+1} + y_o^{M+1}) \qquad \alpha = 1 \tag{11}$$

For the nonuniform cross section, the volume for the tip cell can be found from Equation (8) with $\alpha = \beta\,(M_o+1)$. Since no area exists at section 1, it must be assumed that the depth along the furrow follows from the area power law for section 0. (This assumption allows equation (8) to be used). No other developments are readily apparent. For the intermediate cell, the surface volume is found from

$$V_s = (x_1 - x_o)\,\frac{1}{2}\left[\frac{C_1 y_1^{M_1+1}}{M_1+1} + \frac{C_o y_o^{M_o+1}}{M_o+1}\right] \qquad \text{for } \alpha = 1 \tag{12}$$

Equations (6) thru (12) have been verified by numerical integration.

SUBSURFACE VOLUMES:

In general, the inflow and outflow to each reach of the furrow are not known. Thus, just knowing the total volume of water infiltrated gives little information on how the water is distributed. Information on the distribution of time and volume are necessary to develop an infiltration equation. In a previous work (1), I developed a method for estimating an infiltration function from a volume balance on a single border. This

method assumed spatially uniform infiltration characteristics over the border. Separation of spatial characteristics is beyond the scope of this paper as well, although these techniques could be expended to include some information on spatial variations.

If infiltration into the furrow is not a function of flow depth, then the procedure developed for borders could be used with minor modifications. If the infiltration is affected by flow depth, the equation developed for borders are inappropriate. The general procedure however, is still appropriate. There are two main assumptions that the border method uses to develop an infiltration function. The first is that infiltration functions approximately follow a power function (at least over short ranges). The second is that the average depth infiltrated (over a given wetted distance and irrigation time) plus the associated infiltration opportunity time for that average depth represent the appropriate information to be derived from the analysis (and from which to develop an infiltration function). The border procedure basically starts by assuming a power function of the form

$$z = k\tau^a \tag{13}$$

where z is the infiltrated depth, τ is the opportunity time and k and a are empiracal constants. It is assumed that the constants k and a are the same over the entire border. The total infiltrated volume found from previous computations at any given time is represented by

$$V_s = B \int_0^{x_a} Z(x)dx = Bk \int_0^{x_a} \tau(x)^a dx \tag{14}$$

where B is the border width and x_a is the advance distance (reverts to field length after advance is completed). The only unknowns in Equation 14 are k and a. Two equations are required to solve for the two unknowns. However, an equation exists for each time period (i.e., advance time to each station during advance, and any other time during continuing phase and recession times at each station). Thus each pair of equations can be used to find k and a values. In the border procedure, at each time period values for k and a were determined in combination with all previous time periods. Rather than some numerical average of k and a, the values of opportunity time (from each k and a) were found from the average infiltrated depth at that time, t, being

$$\overline{Z}(t) = \frac{V_Z\ (t)}{Bx_a} \tag{15}$$

The opportunity times were then averaged to determine one point on the infiltration curve.

For the border method, a direction equation (in summation form) was found for the integral of Equation 14. Also, noticing that the constant

k is removed from the integral (or summation) a short cut method was developed to iterate on k and a separately, rather than simultaneously. (Once a value is assumed for a, k is found directly). This method proved efficient since the impact of variation in the value of a is not dramatic. Note also, that if k is a function of x, even if k was assumed constant over each furrow (or border) reach, there are more unknowns than equations (during advance) and no solution for k(x) is available. Allowing a to vary with distance adds further difficulties.

For furrows, this simple method may not be entirely appropriate depending upon how infiltration is described. In any case, numerical integration can be used to develop infiltration constants by trial and error. It would be convenient, however, if direct equations were available, at least for special cases.

Furrow Infiltration

A number of formulations for the effects of infiltration with depth have been developed (2). The most complex is where each new area of soil wetted as the water rises acts as if the infiltration just started. Thus the (cross-sectional) area infiltrated (depth infiltrated times width) is dependent upon the wetted perimeter, W

$$A_z = \int_W z(\tau_s)\, ds \tag{16}$$

where s is the distance along the wetted perimeter and τ_s is the opportunity time at any location s along the wetted perimeter. Since the change in depth over time does not follow a known simple function, this development becomes extremely complex and a solution must be found numerically. Note that A_z replaces $B \cdot z(x)$ in Equation (14).

The next form for A_z assumes that the filtration rate over the wetted perimeter is constant and that the total infiltration rate, dA_z/d_t, is a product of the point infiltration rate times the wetted perimeter

$$\frac{dA_z}{dt} = \frac{dz(\tau)}{dt} W_{(t)} \tag{17}$$

Given the top width from Equation (1), there is no simple expression for wetted perimeter. Thus the W(t) in Equation 17 would have to be found by numerical integration.

One option would be to have a separate function for wetted perimeter. The analysis would follow as for infiltration as a function of top width or

$$\frac{dA_z}{dt} = \frac{dz(\tau)}{dt} B(t) \tag{18}$$

Here B(t), or actually B(x,t), can be determined directly from y(t,x) and Equation (1). Equations for this assumed infiltration relation will be developed after a brief discussion of the remaining methods.

More precisely, Equation (18) should be stated

$$\frac{dA_z(x)}{dt} = \frac{dz(\tau)}{d\tau} B(t,x) \tag{19}$$

The remaining methods are simplifications on this form (or an equivalent form of Equation 17). It can be assumed that infiltration is a function only of upstream (x=0) top width or wetted perimeter

$$\frac{dA_z(x)}{dt} = \frac{dz(\tau)}{dt} W_o(t) \tag{20}$$

where $W_o(t) = W(t,x=0)$ and

$$\frac{dA_z(x)}{dt} = \frac{dz(\tau)}{dt} B_o(t) \tag{21}$$

where $B_o(t) = B(t,x=0)$. Similarly, it can be assumed that infiltration is a function of some constant fixed depth. For wetted perimeter at normal depth for the furrow inflow rate, W_N,

$$\frac{dA_z(x)}{dt} = \frac{dz(\tau)}{d\tau} W_N \tag{22}$$

and for top width at normal depth, B_N

$$\frac{dA_z(x)}{dt} = \frac{dz(\tau)}{d\tau} B_N \tag{23}$$

Other fixed widths that have been chosen are top width and wetted perimeter for 1/2 the furrow inflow rate (4) and top width and wetted perimeter at the furrow inflow rate plus an arbitrary constant of 0.7 ft (3).

<u>Furrow Volume Balance Equations</u>

For the surface volume case, I considered both water surface and surface area shape factors. Here, surface area shape factors have no relevance and will not be considered. The general equations for subsurface volumes are found by integrating Equation (19) over distance and time, or

$$V_z = \int_{x_o}^{x_1} \int_{t_o}^{t_1} B(x,t)i(\tau)dtdx = \int_{x_o}^{x_1} A_z dx \tag{24}$$

for which the infiltration is assumed to vary with top width and where $i(\tau) = dz(\tau)/d\tau$. Now for the tip cell with a uniform cross section, linear advance and a uniform wave front with shape factor β, this becomes

$$V_z = \frac{C y_o^M ka\,(x_1 - x_o)\,(t_1 - t_o)^a}{(\beta M+a)\,(\beta M+a+1)} \qquad \text{for } \beta>0,\ y_1 = 0 \tag{25}$$

$$= \frac{a\,(x_1 - x_o)\,z(t_1 - t_o)B(x_o,t_1)}{(\beta M+a)\,(\beta M+a+1)}$$

where advance is from station 0 to station 1, and t_1 and t_o represent advance times, β is found from Equation (3), a and k are from Equation (12), and C and M are from Equation (1). Over short times and reach length these assumptions are reasonable.

For a nonuniform cross section with intermediate widths represented by Equation (2), the tip cell equation becomes

$$V_z = ak(x_1-x_o)(t_1-t_o)^a \left\{ \frac{C_1 y_o^{M_1}}{(\beta M_1+a)(\beta M_1+a+1)} + \frac{C_o y_o^{M_o}}{(\beta M_o+a)(\beta M_o+a+2)} - \frac{C_1 y_o^{M_1}}{(\beta M_1+a)(\beta M_1+a+2)} \right\}$$

$$\text{for } \beta>0,\ y_1 = 0 \tag{26}$$

For the border method, piecewise linear advance was assumed in the development of a general equation for intermediate cells. This was developed as a recursive equation based on shape factors. For an advancing stream with N cells, the recursive equation for furrows would be (for a uniform cross section and for section infiltration directly related to top width, Equation 19)

$$V_z(t_I) = \frac{a}{(BM+a)(BM+a+1)} \sum_{i=1}^{N} \frac{(x_i-x_{i-1})}{t_i-t_{i-1}} \Big[(t_I-t_{i-1})B(x_{i-1},t_I)Z(t_I-t_{i-1})$$

$$-(t_I-t_i)B(x_i,t_I)Z(t_I-t_i) \Big] \tag{27}$$

where, I represents the current time, t_i is the advance time to station i and t_{i-1} is the advance time to station i-1. In general, this equation does not hold since it assumes a constant known surface shape factor over the entire stream and over the entire irrigation event. This is too restrictive an assumption in many cases. It may lead to erroneous results when the measured interior depths differ too far from those computed by a power law (β) and the furthest upstream depth. In actuality, the equation is only valid when advance is linear (not

piecewise linear). This may lead to additional errors in that it assumes a power law depth hydrograph as well. This may cause errors in relative infiltration from one time period to the next. Thus this equation should only be used for the tip cell and the cell immediately behind it or when the top width effect on infiltration is constant over the irrigation (i.e., Equations 20 through 23). An alternative equation can be developed if we again assume piecewise linear advance and that the change in top width is linear over each time increment. This second assumption is not realistic for the tip cell or the cell immediately behind the tip cell. Note that if infiltration is assumed to vary according to wetted perimeter, then under this assumption wetted perimeter must vary linearly with time. The inaccuracy of using Equation (27) for the cell behind the tip cell is less than assuming a linear change in top width. Thus, Equation (27) can be used for these first two cells (N and N-1). The alternative is numerical integration.

An equation for other intermediate cells can be found, when the top width (or wetted perimeter) is assumed to vary linearly with time at a given station and with distance between stations at a given time, when infiltration varies linearly with top width (or wetted perimeter), and when infiltration follows a power function. This equation is valid for either a uniform or nonuniform cross-section. Because of the change in assumption on the change in depth with time from the first two cells to the latter cells, only the change in volume over a given time interval can be found. This equation is

$$\Delta V_Z(x_i-x_{i-1},t_I-t_{I-1})=\frac{k\Delta x}{\Delta t_a}\Bigg[\frac{\Delta B(t_{I-1})}{\Delta t_a}\{\phi^o(a+2)+\phi^1(a+1)\}+B(x_{i-1},t_{I-1})\phi^o(a+1)$$
$$+\Delta B(x_{i-1})\left\{\frac{\phi^o(a+2)}{\Delta t(a+1)}+\gamma(a+1)\right\}$$
$$+\Delta B\left\{\frac{\phi^1(a+2)}{(a+1)\Delta t\Delta t_a}+\frac{\phi^o(a+3)}{(a+1)\Delta t\Delta t_a}-\frac{\gamma(a+2)}{\Delta t_a}+\frac{(t_I-t_{I-1})}{\Delta t}\gamma(a+1)\right\}\Bigg] \tag{28}$$

(This has not been checked numerically)
where t_a is advance time (eg, $t_a(x_i)$ is the advance time to x_i, it is simply called t_i), Δt_a is the difference in advance time between x_i and x_{i-1}. The terms in Equation (28) are defined as

$$\Delta t_a = t_a(x_i) - t_a(x_{i-1}) = t_i - t_{i-1}$$

$$\Delta t = t_I - t_{I-1}$$

$$\Delta B(t_{I-1}) = B(x_i,t_{I-1}) - B(x_{i-1},t_{I-1})$$

$$\Delta B(x_{i-1}) = B(x_{i-1},t_I) - B(x_{i-1},t_{I-1})$$

$$\Delta B = \Delta B(t_I) - \Delta B(t_{I-1}) = \Delta B(x_i) - \Delta B(x_{i-1})$$

$$\gamma(a) = \frac{(t_I - t_{i-1})^a - (t_I - t_i)^a}{a}$$

$$\overset{n}{\phi}(a) = \frac{[t_I - t_{i-1}]^n}{a}\left\{[t_I - t_{i-1}]^a - [t_I - t_i]^a\right\} - \frac{[t_{I-1} - t_{i-1}]^n}{a}\left\{[t_{I-1} - t_{i-1}]^a - [t_{I-1} - t_i]^a\right\}$$

for $n = 0, 1, 2$

Note that even though Equation (28) appears complex, that only k and a are unknown. With an assumed value for a, ΔV_z and k are linearly related, making a solution for different values for k fairly straight forward. The solution procedure used to solve for k and a is given in (1).

SUMMARY OF TECHNIQUES

The following methods of analyzing infiltration in borders and furrows have been proposed or used to analyze infiltration. This section outlines how the analysis techniques suggested here can be applied to each of these methods.

1. Borders: Use Equation (27), with M=0 and $B(x,t)$ = constant (e.g., 1 foot or border strip width).

2. Furrows where infiltration is not a function of depth:
   Use Equation (27) with M=0 and $B(x,t)$ = constant (e.g., furrow spacing)

3. Furrows where infiltration is a direct function of top width at normal depth for the inflow (Q_0), B_N (Equation 23):
   Use Equation (27) with M=0 and $B(x,t) = B_N$ = constant

4. Furrows where infiltration is a direct function of wetted perimeter at normal depth for the inflow (Q_0), W_N (equation 22):
   Use Equation (27) with M=0 and $B(x,t) = W_N$ = constant

5. Furrows where infiltration is a direct function of top width at normal depth for one half the inflow ($Qo/2$), $B_N(Qo/2)$:
   Use Equation (27) with M=0 and $B(x,t) = B_N(Qo/2)$ = constant

6. Furrows where infiltration is a direct function of wetted perimeter at normal depth for one half the inflow ($Qo/2$), $W_N(Qo/2)$:
   Use Equation (27) with M=0 and $B(x,t) = W_N(Qo/2)$ = constant

7. Furrows where infiltration is a direct function of top width at normal depth plus an empirical constant of 0.7 ft:
   Use Equation (27) with M=0 and $B(x,t) = B_N + 0.7$ ft = constant

8. Furrows where infiltration is a direct function of wetted perimeter at normal depth plus an empirical constant of 0.7 ft. (3):
   Use Equation (27) with M=0 and $B(x,t) = W_N + 0.7$ ft = constant

For these first eight functions, the effective width is fixed for the entire irrigation (both time and distance). Thus the cummulative infiltration and infiltration rate functions are still in direct relation to one another. That is, this constant width can be multiplied to either functional form. Now when the effective width changes with time and distance, the situation is not as simple. Equation (27) applies to the case of a rising water depth where the entire water surface profile follow the same power function (Equation 3) for the entire irrigation. Here the width can be multiplied by the cummulative infiltration function. However, as the depths drop during recession, not only does Equation (27) not apply, but multiplying the cummulative function by the top width is not reasonable, since at the end of the irrigation the depth (and thus area infiltrated) would be zero. As such, Equation (27) is only reasonable when B(x,t) is constant or for very short reaches and time intervals during advance. In the latter case, B(x,t) must be determined from the surface shape factor. Thus, when infiltration is truely effected by width (and flow depth), some function of the width must be multiplied by the infiltration rate rather than the cummulative infiltration function. The remaining methods are based on the integration of width times infiltration rates as shown in Equation (24).

9. Furrows where infiltration is a direct function of top width at the head end of the field, $B(x,t) = B_o(t)$:
   Use Equation (27) for first two advancing cells. Thereafter, Use Equation (28) with $\Delta B(t) = 0$ and $\Delta B = 0$.

10. Furrows where infiltration is a direct function of wetted perimeter at the head end of the field, $B(x,t) = W_o(t)$:
    Use Equation (27) for first two advancing cells. Thereafter, Use Equation (28) with $\Delta B(t) = 0$ and $\Delta B = 0$.

11. Furrows where infiltration is a direct function of local top width, $B(x,t) = B(x,t)$:
    Use Equation (27) for first two advancing cells. Thereafter, Use Equation (28)

12. Furrows where infiltration is a direct function of local wetted perimeter, $B(x,t) = W(x,t)$:
    Use Equation (27) for first two advancing cells. Thereafter, Use Equation (28)

13. Furrows where infiltration starts at time zero for each wetted segment of furrow cross section:
    Use numerical integration, since infiltration rate (over cross-section) depends upon entire history of cross-section wetting (i.e. perimeter over depth hydrograph).

While Equation (28) is based on a power function, similar equations can be developed for other functions. The addition of a constant to the cummulative infiltration function (as in Soil Conservation Service Infiltration Families(3)) does not change Equation (28) since it is applied to the advancing tip where Equation (27) applies. The addition of a constant term to the infiltration rate equation adds only one additional term to Equation (28). For the cummulative infiltration function

$$Z = C + Kt^a + bt \tag{29}$$

Euqation (28) becomes

$$\Delta V_Z(t_I - t_{I-1}) = b\Delta x\Delta t\{B(x_i,t_I)+B(x_i,t_{I-1})+B(x_{i-1},t_I)+B(x_{i-1},t_{I-1})\}/4$$

$$+ \text{ terms on right hand side of Equation (28)} \tag{30}$$

For the case where the effective width changes with time but not distance, (i.e., methods 9 and 10), Equation (30) becomes

$$\Delta V_Z(t_I - t_{I-1}) = \frac{k\Delta x}{\Delta t_a}\Big[\, B_o(t_{I-1})\phi^o(a+1) + \{B_o(t_I) - B_o(t_{I-1})\}\frac{\{\phi^o(a+2)+\gamma(a+1)\}}{\Delta t(a+1)}$$

$$+ b\Delta x\Delta t\{B_o(t_I) + B_o(t_{I-1})\}/2\ \Big] \tag{31}$$

Equation (27) can be applied to any infiltration function.

DISCUSSION:

In the development of equations and solution procedures for borders, k and a were assumed constant over the whole field. This is not generally the case. However, if k and a are assumed to be unknown for each distant increment, then we have 2 times N unknowns, requiring 2 times N equations. It may be reasonable to assume that k varies with location, while a is relatively constant. In this case, there are N+1 unknowns and N equations. Thus, a solution for the k_i and a cannot be found during the advance phase, but can be found after the start of the continuing phase. If a is assumed beforehand, k can be computed during advance. However, this procedure is subject to significant errors in the early part of the irrigation since the surface volume at the tip cell is only roughly approximated.

SUMMARY:

Equations for subsurface volume have been developed for infiltration under furrow irrigation for a variety of infiltration/flow depth relationships. Also, developed are equations for the surface storage in the furrow during an irrigation from measured water depths and cross-section shapes. From this and measurements of inflow and outflow, the subsurface volumes over time can be determined and used with the subsurface volume equation to determine infiltration equation constants. These equations allow for variable furrow cross-section with distance and several schemes for varying infiltration with flow depth. The potential exists for determining the variation in infiltration constants with

distance, but probably not to a high degree of accuracy. This work is an extension of prior work in borders.

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ACKNOWLEDGEMENTS:

The author would like to thank Dr. Theodor Strelkoff for verifying the surface volume balance equations by numerical integration.

TITLE: PROGRAM FOR COMPUTING FLUME RATING TABLES

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION

Most structures built for the purpose of measuring or regulating the rate of flow (Q) in irrigation canals and natural streams consist of a converging transition which guides the accelerating water into a throat where it further accelerates to supercritical flow, and a downstream transition where the flow velocity is reduced to an acceptable subcritical velocity (see Figure 1).

Upstream of the structure is an approach channel in which the water surface must be sufficiently stable to enable a good reading of its elevation. Downstream from the structure is a tail-water channel, which is fundamentally important to the design of the structure because the range of tailwater levels that will result from varying flow rates determines the elevation of the crest of the throat with respect to the tailwater channel bottom, P2.

The difference in elevation between the crest of the throat and the water level in the approach channel is called the upstream sill-referenced head (SH1). That part of the approach channel where this water surface elevation is measured is called the head measurement section or gauging station. The hydraulic theory of critical flow associated with long-throated flumes has been known for more than a century. However, most flumes require an empirical discharge coefficient or a laboratory calibration in order to determine the stage-discharge relation. A mathematical model was recently developed which allows the prediction of this stage-discharge relation and the related head loss requirement, which is valid if the length of the flume throat, TL, is long with respect to the upstream sill-reference energy head, H1. The model is accurate to $\pm 2\%$ within the range $0.075 < H1/TL < 0.75$. Such measuring devices often are named "long-throated flume" and "broad-crested weir", which from a hydraulic point of view are very similar. These long-throated devices have a number of advantages over other devices in terms of predictability, adaptability, low head loss requirement, and relatively low cost. The purpose of this article is to provide a BASIC computer program useful for the design and calibration of these devices.

The Model

For an ideal frictionless fluid, there is a unique relationship between the sill-referenced energy head at the head measurement section (H1) and the ideal rate of flow (QI) through a control section of known shape where critical flow exists. A trial and error solution is necessary to obtain a relationship between the sill-referenced head (SH1) and QI, since the relationship between SH1 and H1 varies with the shape of the approach channel. This trial and error solution is relatively simple and converges quickly (convergence is actually performed on the critical depth, YC, provided that the flow area in the throat, AC, is less than that in the approach section, A1). A flow chart of the procedure is

shown in Figure 2, where Y1 = flow depth in approach channel and TC = top width of flow at the control section.

For real fluids, the discharge varies from that computed above due to frictional energy losses, non-uniform velocity profiles and streamline curvature. A mathematic model has been developed which will account for most of these effects. This model is presented in a recent book which also includes rating tables for standard flumes, design procedures and construction methods (1). This model is presented here in BASIC.

Other limitations are that the Froude number in the approach section (FR1) be less than 0.45 and that the ratio of convergence to the flume throat (EN) be approximately 3 to 1 (horizontal to vertical). (For variations on these limits, see Reference 1).

The model also calculates the energy loss across the structure required for maintaining critical flow in the flume throat. This energy loss is expressed in terms of the modular limit which is the ratio of the downstream to upstream energy head (H2/H1) at which the tailwater level begins to affect the stage discharge relationship. Modular flow exists when the stage-discharge relationship is not affected by the tailwater level. We recommend the use of either a sudden rapid expansion (EM = 0) or a gradual expansion at between 4 and 6 to 1.

The Computer Program

The program input is given in Table 1. The flume dimensional variables are defined in Figure 3. The data entered in line 90 define the cross-sectional shapes at the three cross sections of Figure 3. Different shapes can be used by modifying the functions for area, top width, and wetted perimeter (lines 20 through 70). The second data line defines the flume profile and the material roughness k (see Table 2). An approximate roughness value is sufficient (e.g., within one order or magnitude) unless the roughness is relatively large (say 1%) with respect to the flow depth. The last data line (120) gives the initial value of SH1 for which a calibration is desired, the increment for successive values of SH1 and the highest value of SH1.

The input variable names were used to provide consistency between this program, expanded program in the FORTRAN language and with the theory presented in Reference (1). The program has been written to follow the computational procedure presented in Chapter 9 of Reference (1). The routines used converge very rapidly for flumes which operate as intended. Thus the relative error used to check convergence has been set very low. Typically 5 to 10 iterations are sufficient. When there is not enough of a contraction in flow area from the approach channel to the flume throat or not enough expansion in flow area from the throat to the tailwater channel, the routines used will not converge. A counter was added to these routines to terminate execution after 100 iterations.

The output from the computer program includes a number of items of interest. The input data on flume cross sections and profile is

repeated, along with additional calculated profile information. The output table consists of; the head versus discharge relationship, SH1 and Q; the Froude number in the approach channel, Fr_1; the ratio of H_1/TL; the resultant values of discharge and velocity coefficients, CD and CV; the required energy loss, DH, for maintaining modular flow; the maximum allowable tailwater level, Y2, for maintaining modular flow; and the modular limit, ML.

The program currently operates in metric units. It can be made to operate in English units by changing the values for the acceleration of gravity and the kinematic viscosity as indicated in line 295. (Be sure to change the m to ft in the output formats also.)

SUMMARY:

A computer program has been written in the BASIC language which can be used to develop rating tables and assist in the design of long-throated flumes and broad-crested weirs. The program is based on the theory presented in a book recently published on the subject. It has several improvements over previous BASIC versions in that convergence routines are improved and headloss and modular limit calculations were added. The program listing with instructions for use are included.

BOS, M.G., REPLOGLE, J.A. and CLEMMENS, A.J. 1984. Flow Measuring Flumes for Open Channel Systems. John Wiley & Sons, NY. 321 pp. (published)

Personnel: A.J. Clemmens and J.A. Replogle

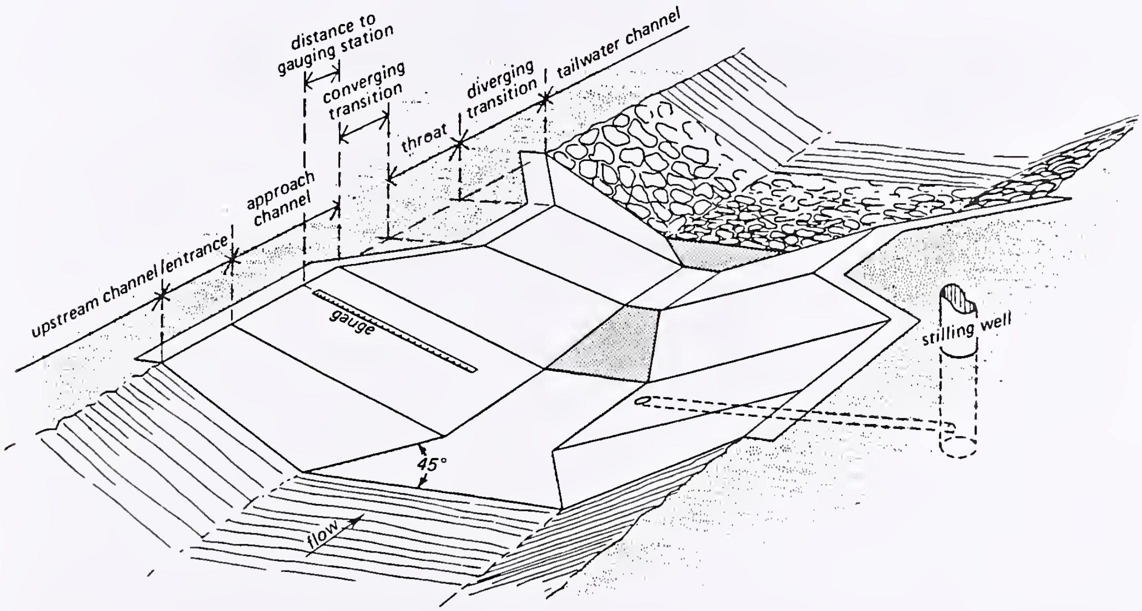

Figure 1. General layout of a flow measuring weir or flume.

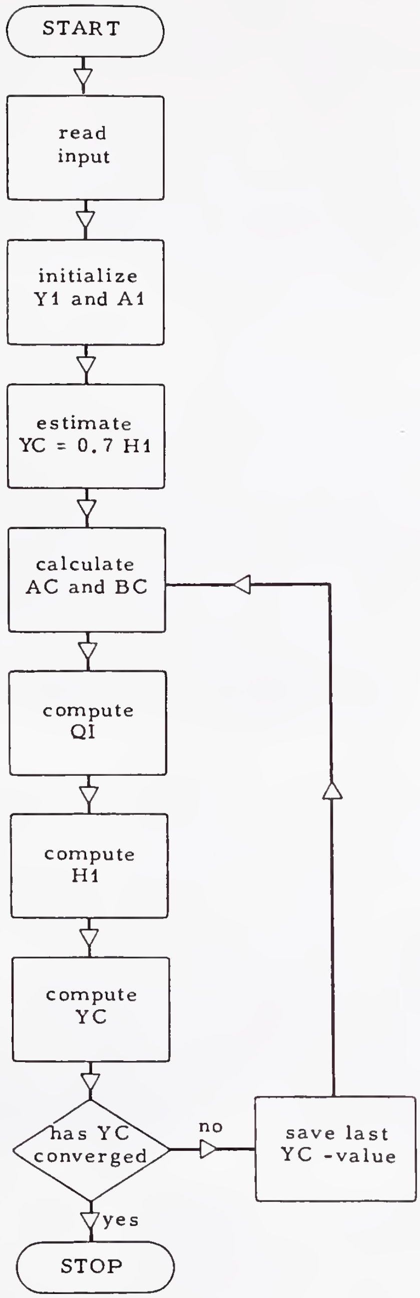

Figure 2. Flow chart for ideal flow calculations.

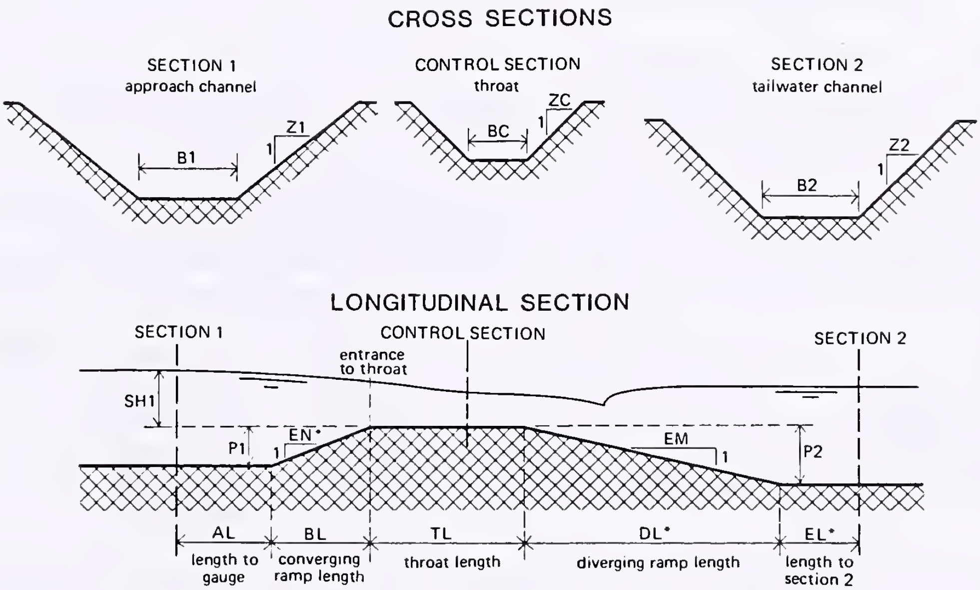

Figure 3. Definition of terms used as input data for computer program. (* Not specified by user).

Table 1. Input data for computer program. Refer to Figure 3 for definition of terms. All dimensions in meters.

Line		
90	B1, Z1, BC, AC, B2, Z2	
105	AL, BL, TL, P1, P2, EM, K	
120	Start, increment, limit	on value of SH1

Table 2. Absolute roughness of materials used in flume construction.

Material	Range of K Absolute Roughness Height in m
Glass	0.000001 - 0.000010
Metal - painted or smooth	0.000020 - 0.000100
- rough	0.000100 - 0.001000
Wood	0.000200 - 0.001000
Concrete - smooth troweled	0.000100 - 0.002000
- rough	0.000500 - 0.005000

TITLE: EFFECTS OF NON-LEVEL PLACEMENT ON THE CALIBRATION OF LONG-THROATED FLUMES

NRP: 20740 CRIS WORK UNIT: 5422-20740-003

INTRODUCTION:

Several flow measuring flumes have been developed by Bos, Replogle, and Clemmens (1984) for use in irrigation canals and natural streams. Smaller portable versions have also been developed for use in single irrigation furrows for flow survey work (Clemmens, et al., 1984). Rating tables showing stage-discharge relationships can be generated for these flumes with a computer model described in Bos, et al., 1984. Although rating tables have been generated for several standard-sized flumes, any appropriately proportioned shape and size can be calibrated using the computer model. The flexibility of this model allows irregularities in field construction to be accommodated in the flume calibration by using post-construction field dimensions. The resulting rating tables are accurate to within ± 2 percent of the actual discharge (Replogle, 1978).

A field condition not directly considered in the modeling procedure is that of a sill crest which is not level in the direction of flow. All modeling computations assume a level crest. However, field construction and placement procedures frequently result in non-level crests that affect the flume calibration. These effects were studied and guidelines developed to minimize the net error that results from such non-level construction or flume placement.

Laboratory Procedure

To study the effects of a non-level sill crest on the flume calibration, a small portable RBC flume (Figure 1) with a crest width b_c = 100 mm (Clemmens, et al., 1984) was tested on eight different slopes with four discharges at each slope.

The energy relationship that allows computation of discharge from the flume dimensions requires knowledge of the sill referenced head h_1, which is the water surface elevation above the sill crest at a location far enough upstream not to be in the major drawdown portion of the water-surface profile over the sill (Figure 2A). For the RBC flume used, this distance is $0.5b_c$ = 50 mm upstream from the start of the ramp. A sidewall gauge is placed at this location that is marked in discharge units to allow direct discharge reading by observing where the water surface crosses the gauge. Existing theory on effects of non-level flume placement suggests that a translocated stilling well for the h_1 measurement be placed as close as practical to the control section on the sill with tubing connecting it to a pressure tap at the sidewall gauge location. This translocating of the stilling well is expected to minimize the error from non-level flume placement.

Downward slopes in the direction of water flow are defined as positive and upward slopes are defined as negative. Negative slopes are also called adverse slopes. Eight slopes were selected at ± 1%, ±1.6%, ±2.6%, and ± 3.6%. Four discharge rates were used that represented the

middle range of discharges normally measured with this style and size of flume. The flow range for this flume is 0.2 to 8.7 l/s. The flows tested ranged from 2.04 to 4.03 l/s. This represented an H/L range of 0.31 to 0.45 (H is the total upstream head and L is the crest length in the direction of flow). This relatively narrow test range was somewhat dictated by laboratory limits on detection sensitivity at low flow rates, and on flow surface instabilities at the higher ranges that significantly masked the effects we were trying to observe. Each discharge rate was established using a weigh tank and a stop watch and with the flume in a level position. Sill referenced head readings h_1 were then taken from the translocated stilling well and the flume adjusted to each of the eight slopes before the discharge was changed. The h_1 readings were used with the stage-discharge rating table to get the "apparent" discharge for each slope for comparison to the laboratory calibration as measured by the weigh-tank procedure. The laboratory measurements for all slopes are listed in Table 1, where h_1 is the sill referenced head as measured in the translocated stilling well that was mounted at the outlet of the flume, Figure 2. The apparent discharge Q_a obtained from the stage-discharge rating table as if the flume were level is listed with each h_1 reading. For example, if the flume were arbitrarily placed in the field to measure discharge and was unknowingly placed at a slope of +2.6%, and the user read 54.3 mm at the translocated stilling well, assuming the flume to be level, he would determine from the rating table that the flow was 2.79 l/s. This is the apparent discharge, Q_a. The laboratory data in Table 1 show that for a slope of + 2.6%, and Q_a of 2.79 l/s, the weight-determined discharge Q_W is 2.62 l/s. Had the flume actually been placed level, the user would have been expected to closely approximate Q_W. This error in the reading was calculated in the usual manner, that is,

$$E = \frac{Q_W - Q_W}{Q_W} \times 100 = \frac{2.79 \text{ l/s} - 2.62 \text{ l/s}}{2.62 \text{ l/s}} \times 100 = 6.5\%$$

The discharge-reading error, E, as a function of Q_W for the eight slopes tested are shown in Figure 3.

The error in discharge measurement from a non-level flume is magnified and reversed in sign if the discharge is read from a wall-mounted gauge placed near the stilling well tap location (Figure 1). If our hypothetical user from the previous example had simply read this gauge instead of using the stilling well h_1 reading, he would have read a Q_a of 1.99 l/s which is 23.9% less than Q_W. (This reading for Q_a is geometrically consistent with the translocated stilling-well reading using the direct geometric relation between the stilling well and the gauge location due to the slope). This error that would result from reading the sidewall gauge in a non-level position is shown in Figure 4 for the slopes and discharges tested. Also shown in Figure 4 are the computer model predictions of the deviations from the level-flume readings after certain geometric adjustments, described below, were incorporated to account for changes in the approach channel area and for the shift in the zero-reference for the wall gauge. This will be mentioned in more detail later. Note that the predictions are better for the adverse slopes.

Comparison of Figures 3 and 4 shows the relative advantage of using the translocated stilling well to determine the discharge rate through these portable flumes.

ANALYSIS

When the flume is placed in a non-level position, several changes occur in the calibration that are not fully accounted for in the computer model. There are two strictly geometric changes that directly alter the flume calibration. Both the h_1 measurement as read from the translocated stilling well and the upstream approach channel area are changed. If the slope of the flume is known, these geometric changes can be accounted for mathematically. Another change that alters the flume calibration is an apparent movement of the control section on the sill crest. The control section as used here is defined as the section across the flow through which downstream disturbances are not transmitted upstream and usually appears to occur at about one-fourth of the crest length from the downstream end of the sill on a level flume. However, it is suggested that the control section changes position when the flume is sloped (Bos, et al., 1984). This was investigated by using the laboratory calibration data at the known slopes and comparing these with calibrations produced by the computer model with the geometric adjustments for slope incorporated.

A profile of a level flume crest is shown in Figure 2A where h_1 is the sill-referenced head at the gauging station that is also reproduced in the translocated stilling well when the flume is level, and p_1 is the sill height. Figures 2B and 2C illustrate approximate profiles of sloping flumes. Figure 2B shows the relationship between the measurement error Δh_1 (that results when h_1 is read directly from the stilling well), the apparent head reading h_a, and the sill referenced head h_1, or

$$h_1 = h_a - \Delta h_1$$

Expanding this simple expression in terms of the slope angle ϕ,

$$h_1 = h_a \cos\phi + D_C \sin\phi \qquad \text{for the adverse slopes,}$$

and

$$h_1 = h_a \cos\phi - D_C \sin\phi \qquad \text{for the positive slopes,}$$

where D_C is the distance from the stilling well centerline to the control section, Figure 2A.

The stilling well head readings, h_a, were adjusted for the slope resulting in the h_1 values which were used with the stage-discharge rating table to determine the discharges. The remaining deviation from the laboratory calibration is shown in Figure 5. Comparing Figure 5 with Figure 3 shows the reduction in error of the indicated discharge rate due to simply making the geometric adjustments for a known installed slope. The errors plotted in Figure 5 appear to be random and within $\pm$ 2% for small positive slopes and for all of the adverse slopes for the higher flow rates shown. This same trend is expected to continue to yet higher flow rates.

Figure 2C shows the increase in the upstream approach channel area for an adverse sloping flume. The sill height, p_1, is increased relative to the gauging station. Conversely, this area and the sill height decrease for positive slopes. Since the sill height for the flume tested was 50 mm, the adjusted sill height, p_1, is

$$p_1 = 50 \text{ mm} + D_g \sin \phi \quad \text{for the adverse slopes,}$$

and

$$p_1 = 50 \text{ mm} - D_g \sin \phi \quad \text{for the positive slopes,}$$

where D_g is the distance from the gauging station to the control section, and ϕ is the slope in degrees.

Having applied the mathematical adjustments for the geometric changes in the flume, the remaining deviation from laboratory calibration was accredited to movement of the control section along the sloping sill. When the flume is placed at an adverse slope the control section is thought to move downstream, and conversely, for positive slope, it is believed to move upstream (Bos, et al., 1984).

The suggested geometric adjustments for h_1 and p_1 were made assuming that the control section was at one-fourth of the crest length from the downstream end of the sill. In Figure 2C, which shows a flume on an adverse slope, visualize the control section sliding up and down the sill from the originally assumed quarter-point location. As it moves toward the upstream end of the sill, h_1 increases and p_1 decreases in magnitude. In order to evaluate this possible control section movement, the h_1 and p_1 adjustments were computed for four locations on the sill and these values then used in the computer model for further comparison with the laboratory calibration. Locations, A, B, C, and D are indicated in Figure 6. The discharge deviations from laboratory calibration are shown for an example slope of + 3.6% in Figure 7.

In Figure 7, note that the curve corresponding to a control section location at point B crosses the zero-error line at a discharge rate of approximately 2.6 l/s. This means that the computer-model prediction would closely match the laboratory calibration at this discharge and control section location. Curves A through D in Figure 7 represent a family of curves, each corresponding to a point on the sill. For example, at the weighed-discharge rate of 2.04 l/s, there is a point on the sill, in this case between points A and B, that if used in the computer model would produce a zero-difference calibration value. This curve is shown as a dashed line in Figure 7. Similarly, following the zero-error line from the weight-discharge rates of 2.04 l/s through 2.62 l/s to 4/0 l/s, the point on the sloping sill required to match the laboratory calibration can be determined. In this way the assumed control section movement can be traced on the sill for the range of flows tested. For example, at the illustrated slope of + 3.6%, the control section appears to move from a point approximately midway between points A and B at the lowest tested flow of 2.04 l/s to a point approximately midway between points B and C at the highest tested flow of 4.0 l/s. The control section thus appears to move downstream with increasing discharge at any fixed positive slope as shown schematically

in Figure 6. The apparent movements for five other slopes, determined in a similar manner, are shown in Figure 8.

Notice in Figure 8 that for an adverse slope the control section moves upstream with increasing discharge and for a positive slope the control section moves downstream with increasing discharge. Also, the movement of the control section is less pronounced for adverse slopes than for positive slopes as indicated by the smaller range between the control-section locations for the low and high test-flow rates.

The concept of control-section movement appears to explain the deviations between level-flume calibrations and those with only simple geometric adjustments for sloping flumes. Although the control section seems to move with changing discharge, the effects are much less significant on level flumes because p_1 and h_1 do not change with control-section movement. It should be pointed out that the apparent locations of the control sections shown in Figure 8 should be regarded as approximate because the procedure necessary for their locations is not precise. For example, for the narrow range of flows tested, the location for the level flume seems to deviate substantially from the assumed downstream quarter-point. It is because of these imprecise procedures, however, that no great significance is placed on the exact control section location as shown, but rather on the relative locations throughout the range of slopes and discharges. Thus, the original quarter-point assumption is retained.

DISCUSSION:

The laboratory data show that a non-level flume crest can cause large errors in discharge measurement, particularly when the sidewall gauge is read on the portable RBC flume (see Figures 3 and 4). Mathematical or calibration corrections can only be applied when the slope is known. In practice, slopes are a result of construction or placement errors that may not be known to the user. Therefore, user guidelines or techniques need to be employed to reduce the chances for non-level flume placement.

For proper employment, the sill-referenced head h_1 must be measured with reference to the control section on the sill crest. As mentioned previously, this control section is generally assumed to occur at about the quarter-point from the end of the sill crest. This is a reasonable assumption for level flumes. However, as shown in Figure 8, the control section appears to move considerable when the crest is not level in the direction of flow. In the case of a positive slope, the control section can appear to move to the extreme upstream end of the sill crest at low discharge rates. Methods of head detection that minimize these slope effects are desirable. If a stilling well could be placed directly on the sill at the control section, and could move with the changes in the controll-section location, the h_1 readings would be correct for all slopes and flows. This was essentially the mathematical adjustment process that was applied to the h_1 and p_1 values. Obviously, placing the stilling well at the control section would disrupt the straight line flow required for proper flume functioning, although, suspending a vertically movable cup above the flow has been successfully employed on larger spe-

cial purpose portable flumes (Replogle, and Clemmens, 1979). Attempting to move such a suspended cup in a horizontal direction to follow the assumed control section movement would appear to be impractical. For these reasons the stilling well in the portable RBC flumes is placed as close to the assumed control section as practical. When the stilling well is placed on the centerline of the flume near the downstream end of the sill crest, the effects of non-level placement are reduced and the stilling well is far enough beyond the control point to cause no detectable back pressure effects, if its diameter is less than about 25% of the crest width (Clemmens, et al., 1984). Figure 3 indicates that even with a translocated stilling well, discharge measurement errors are still in excess of the desired 2% accuracy with only a 1% slope, which is about 6.1 mm rise over the 610 mm length of the flume. To assure the possibility of 2% to 3% accuracy it is recommended that the flume be leveled with a carpenter's level in both directions, i.e., parallel and perpendicular to the flow direction, and that the translocated stilling well be used to determine the h_1 readings. Only when larger errors can be tolerated should the flumes be leveled by eye and the discharge read from the wall gauge in the usual wall-gauge location. Refer to Figure 4 to gain an appreciation of the probably magnitude of error obtainable by improper placement. Note that adverse slopes cause larger deviations than equivalent positive slopes when read from the sidewall gauge, but that the reverse situation exists when read from the stilling well, Figure 3.

Some of the effects of longitudinal slope can be averted by placing the translocated stilling well on either side of the flume, but at the assumed control-section location at the quarter-point in the longitudinal direction. This would eliminate the Δh adjustment (Figure 2B, 2C), provided that cross slope were carefully controlled.

In an irrigation canal with a permanent flume it is desirable to read the discharge directly from the sidewall gauge. Because of the permanency of the structure, slight sidewall construction irregularities can be compensated for in the wall gauge placement. To minimize these errors the wall gauge should be zeroed to the flume crest by use of a surveyor's level. Additionally, the rod reading should be calculated for the most commonly expected discharge. The wall gauge may then be readjusted slightly at that discharge reading level. This will assure highest accuracy at common flows and relegate the larger discrepancies to lesser used ranges of the gauge. Crest levelness and wall gauge placement are the two most critical considerations in flume construction (Bos, et al., 1984).

SUMMARY AND CONCLUSIONS:

Tests were conducted to study the effects on the calibration of long-throated flumes caused by non-level placement or construction, and guidelines were developed to minimize these effects. Mathematical adjustment for the non-level, sill-referenced head h_1 and apparent sill height p_1, were used as input into a computer model for recomputing flume calibrations. Deviations from the original level calibration could be accounted for by reasonable shifts in the location of the

control section on the sloping crest that in turn resulted in adjusted sill-height, p_1, and head, h_1, values. The procedure for these adjustments produces an approximate mapping of the control section movement for positive and adverse longitudinal slopes for various discharges. In general, the control section apparently moves upstream with increasing discharge for adverse slopes which causes less deviation from the level-flume calibration than positive slopes.

This study provides quantitative support to previously qualitative recommendations, tending to confirm the assumptions and construction recommendations suggested by Bos, et al., 1984, for long-throated flumes in general, and for portable flumes in particular. These guidelines for flume placement to minimize the chance of discharge-reading errors caused by a non-level sill crest are:

A. Portable RBC flumes:

   1. Use translocated stilling well for head, h_1, measurements, whenever practical.

   2. Level the flume with a carpenters level in the directions perpendicular and parallel to the flow.

B. Permanent cast-in-place flumes:

   1. Zero the sidewall gauge to the flume crest using a surveyor's level, or equivalent means.

   2. Take special care during construction to assure a level sill crest.

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PERSONNEL:

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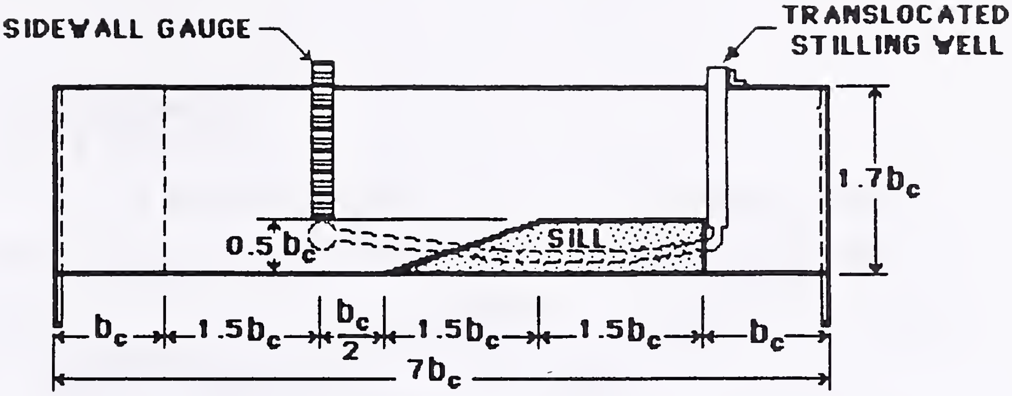
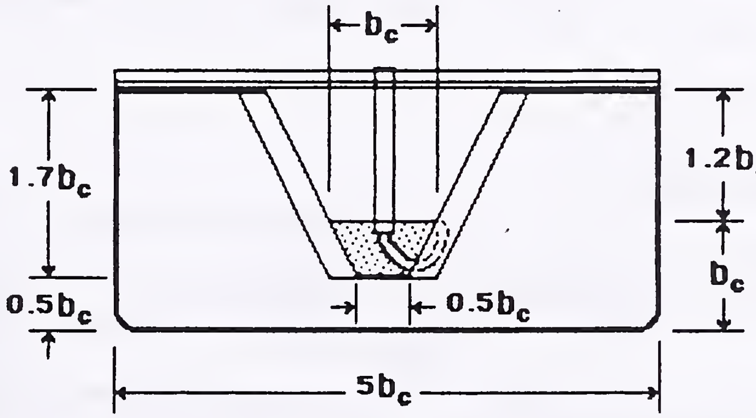
TABLE 1. Laboratory calibration, Q_w, and apparent discharge, Q_a, at various slopes.

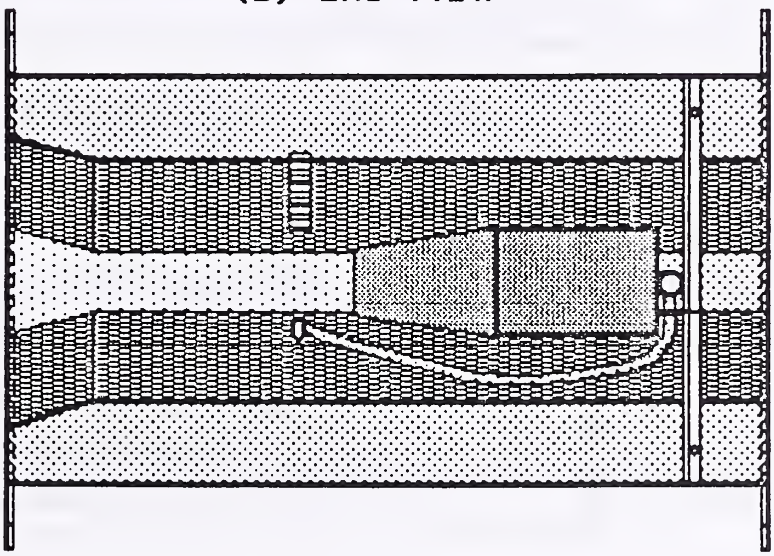
Slope	(Head Readings and Corresponding Discharges)				
+3.6%	h_1(mm) =	49.8	55.5	61.0	68.0
	Q_a(l/s) =	2.39	2.90	3.45	4.20
+2.6%	h_1(mm) =	48.8	54.3	60.3	68.0
	Q_a(l/s) =	2.31	2.79	3.37	4.20
+1.6%	h_1(mm) =	-----	53.8	59.5	67.0
	Q_a(l/s) =	-----	2.74	3.29	4.09
+1.0%	h_1(mm) =	46.8	53.3	59.3	66.5
	Q_a(l/s) =	2.14	2.70	3.27	4.03
0.0%	h_1(mm) =	46.0	52.5	58.5	66.0
	Q_a(l/s) =	2.08	2.63	3.17	3.98
-1.0%	h_1(mm) =	45.0	51.5	78.0	66.0
	Q_a(l/s) =	2.00	2.54	3.12	3.98
-1.6%	h_1(mm) =	44.5	51.5	57.8	65.5
	Q_a(l/s) =	1.96	2.54	3.12	3.92
-2.6%	h_1(mm) =	44.3	51.0	57.3	65.5
	Q_a(l/s) =	1.94	2.50	3.07	3.92
-3.6%	h_1(mm) =	44.0	50.8	57.0	65.3
	Q_a(l/s) =	1.92	2.48	3.05	3.90
0% Lab. Calibration	h_1(mm) =	46.0	52.5	58.5	66.0
	Q_w(l/s) =	2.04	2.62	3.21	4.03



(A) SIDE VIEW, SECTION ALONG CENTERLINE



(B) END VIEW



(C) TOP VIEW

Figure 1: General dimensions for portable RBC flumes.

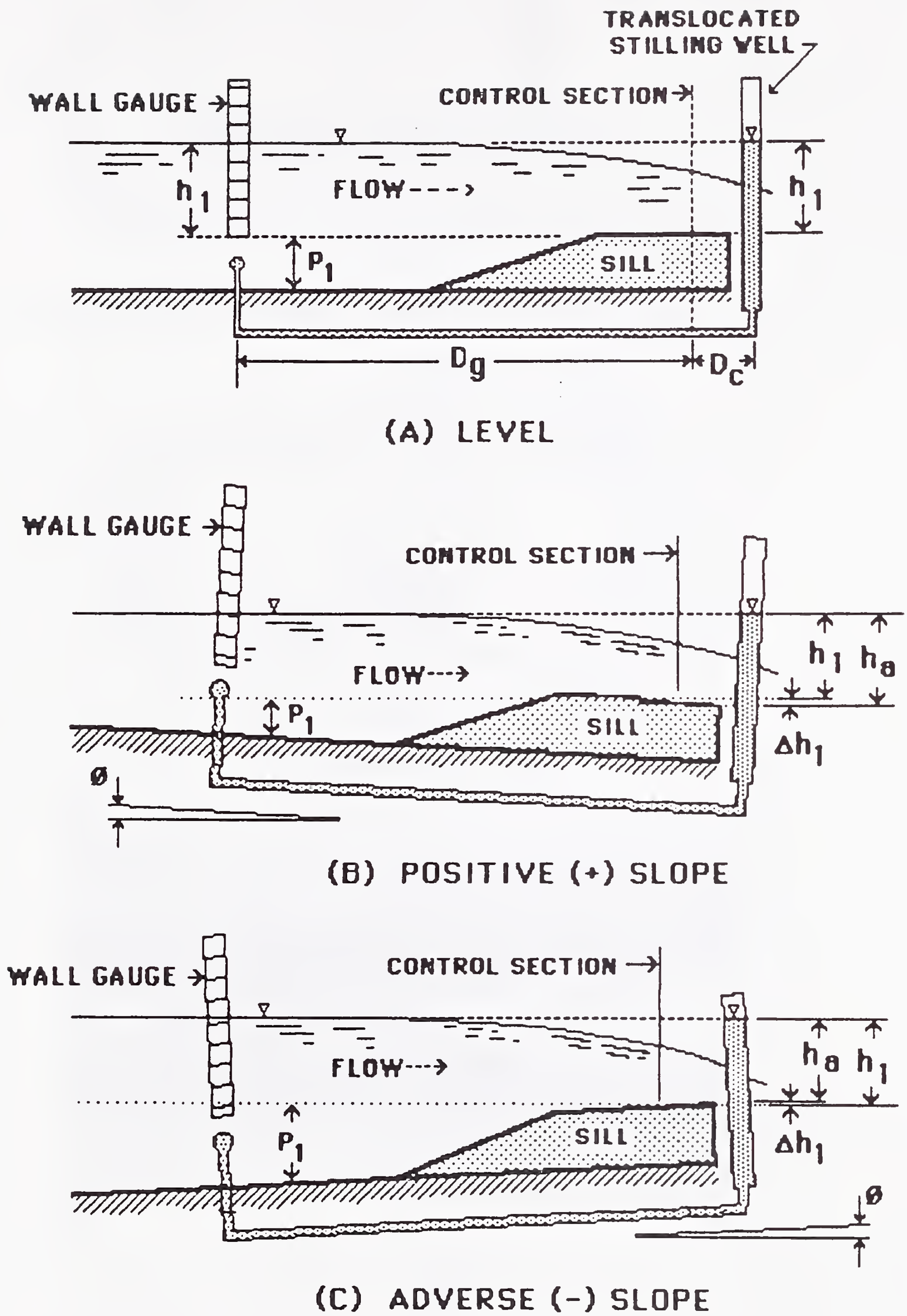


Figure 2. Schematics of flow through flume on level, positive and adverse slopes.

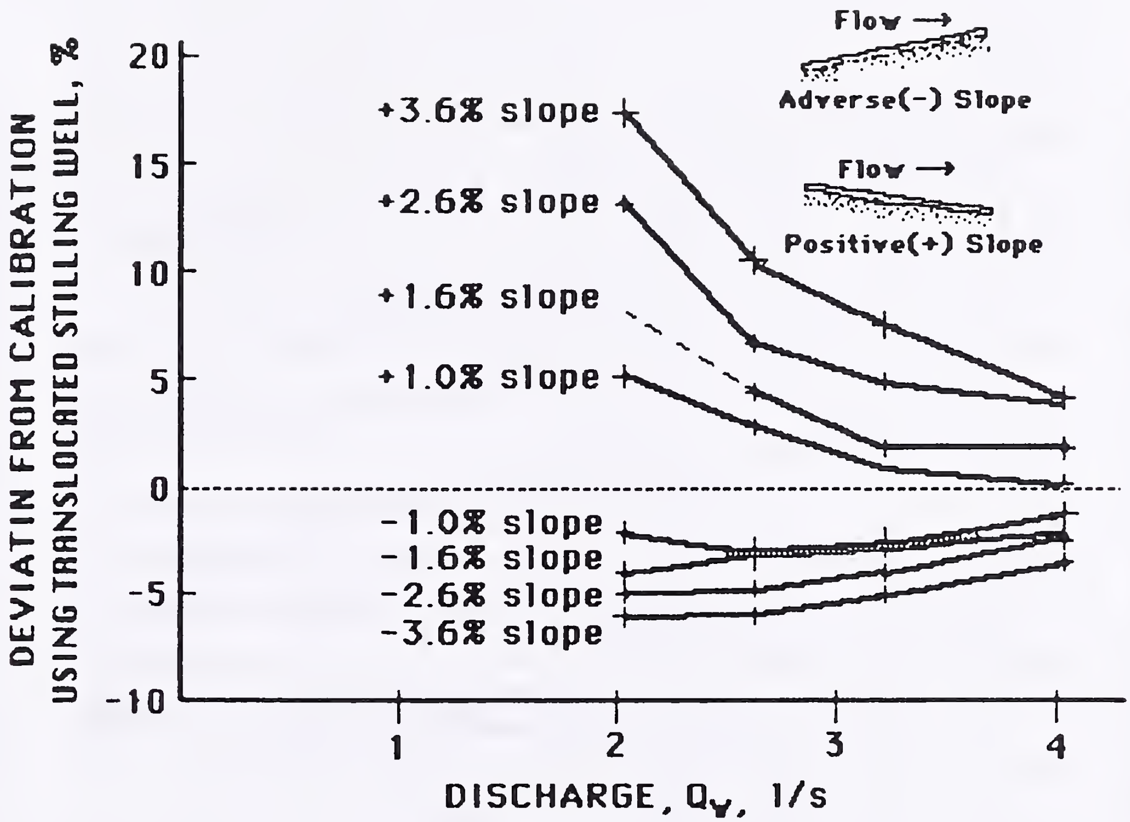


Figure 3: Deviation from calibration as detected by the translocated stilling well.

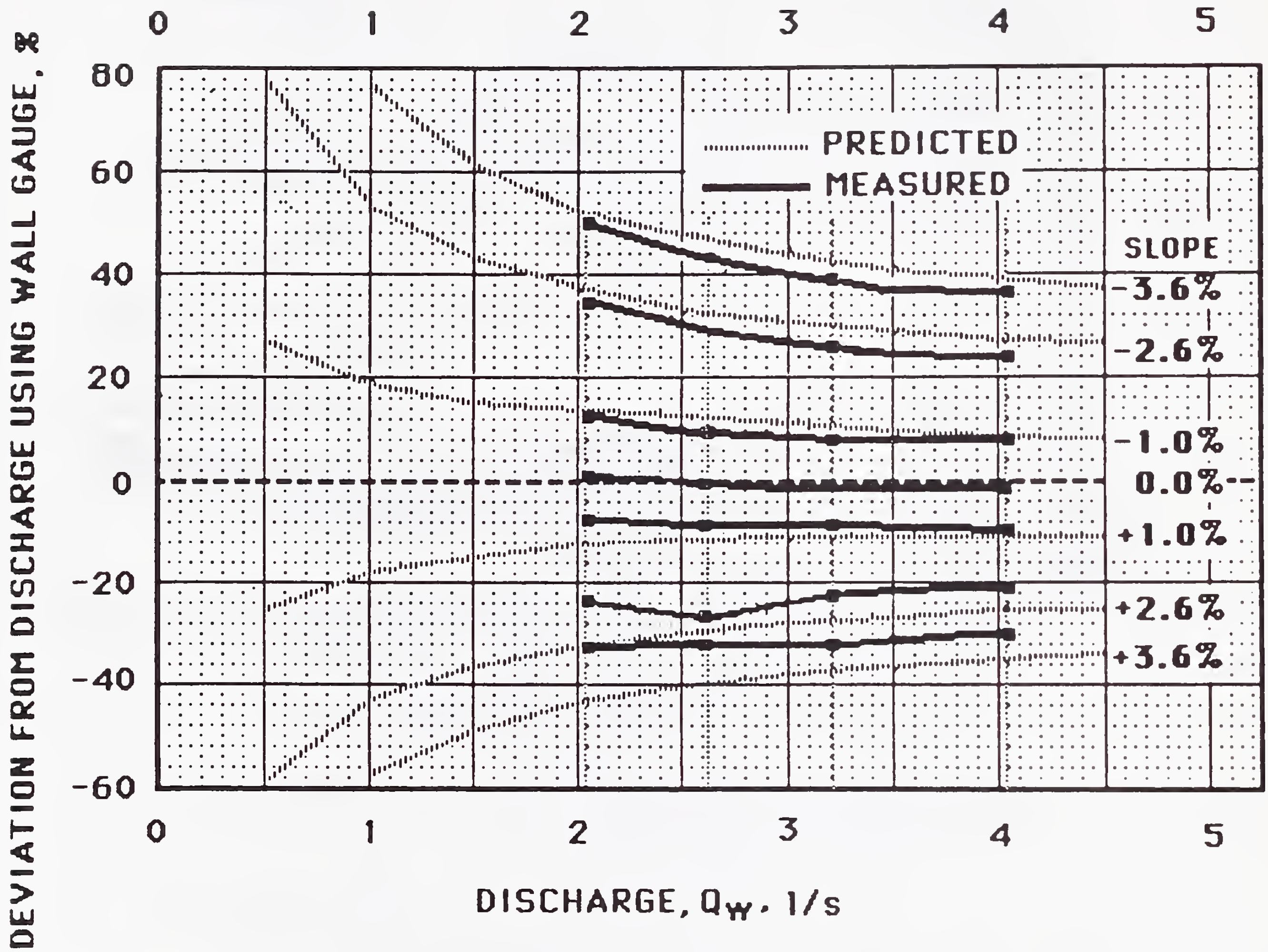


Figure 4: Deviation from calibration using an upstream sidewall gauge that was previoulsy zeroed to the sill elevation at zero slope. The computer model predictions of the deviations are also shown.

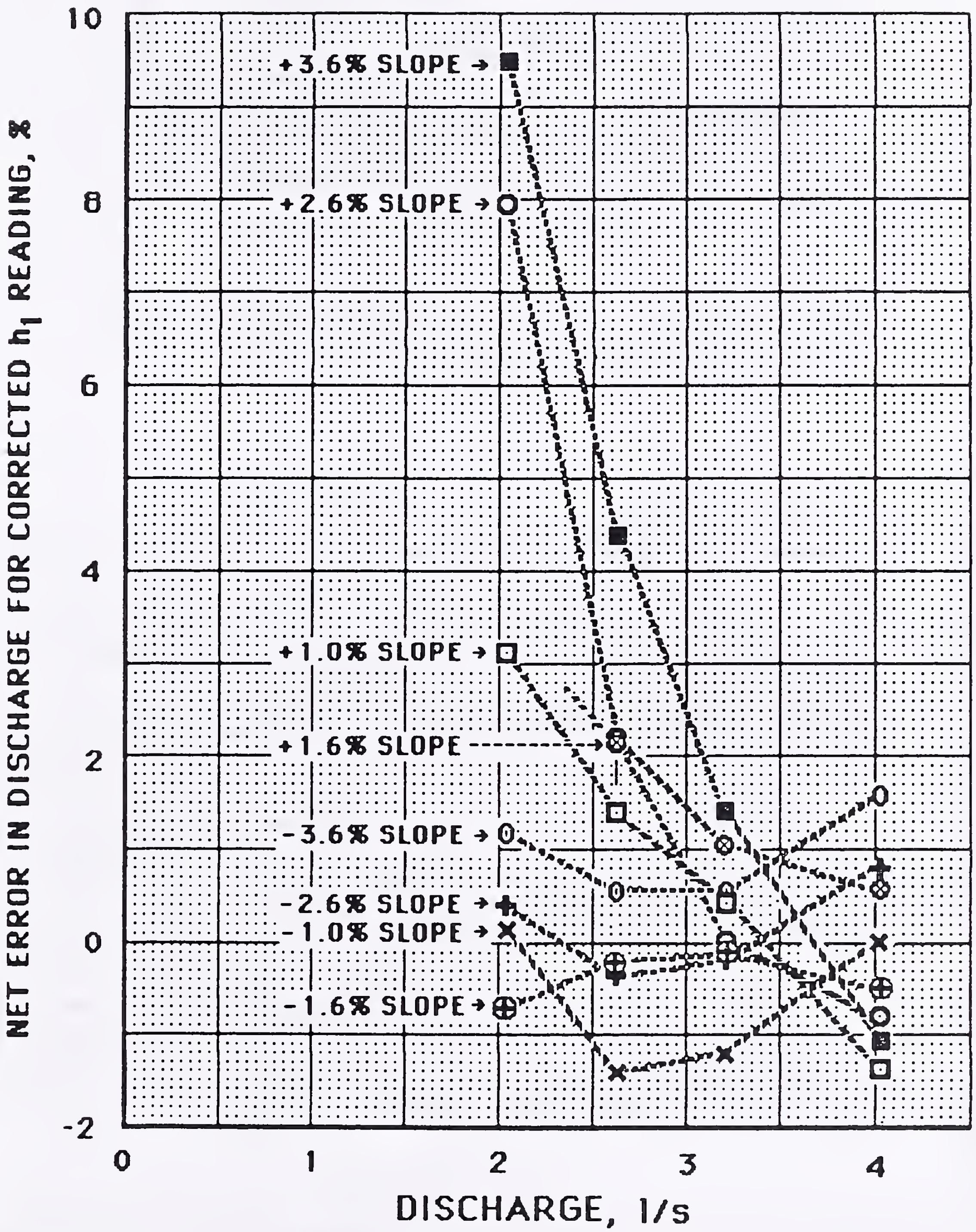


Figure 5. Deviation from calibration for various slopes with gauges (wall gauge and translocated stilling well) re-zeroed to elevation of sill quarter-point (Point D, Figure 6) for each slope.

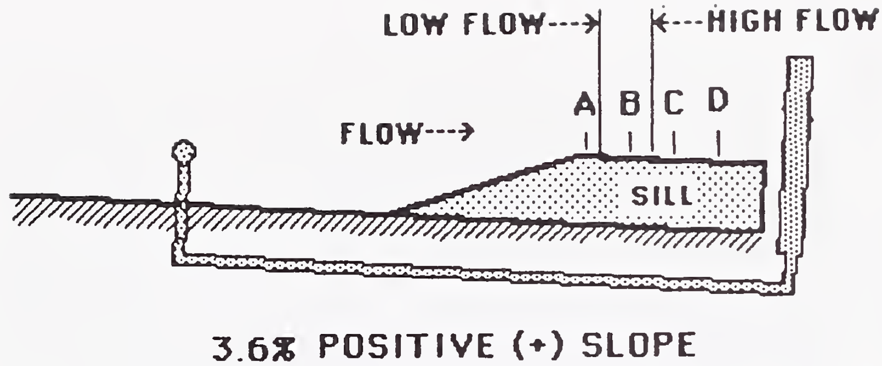


Figure 6: Apparent movement of control section with changing discharge for +3.6% slope.

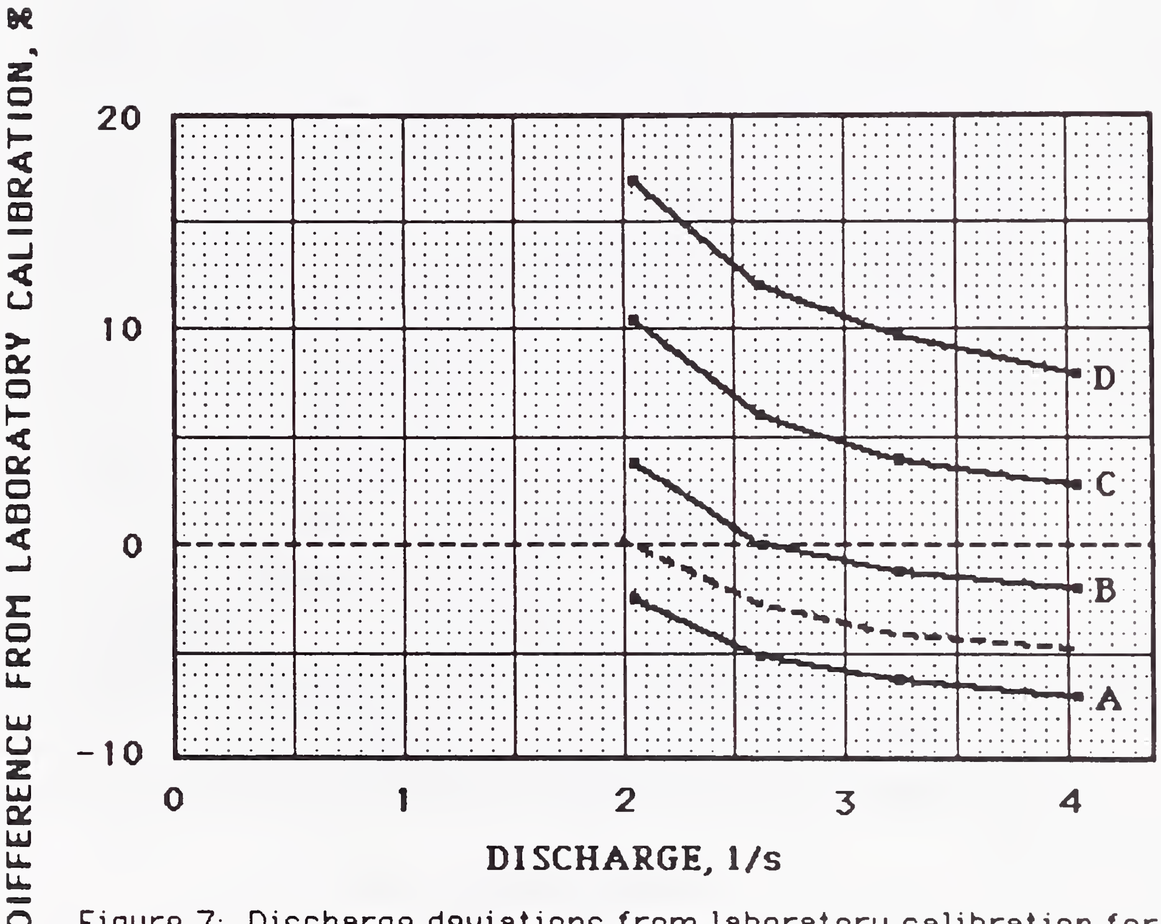


Figure 7: Discharge deviations from laboratory calibration for an example slope of +3.6% after geometric adjustments for the slope. Note that for a selected discharge of 2 l/s (Q_W/Q_{max} = 0.235), zero deviation lies between A and B (Figure 6).

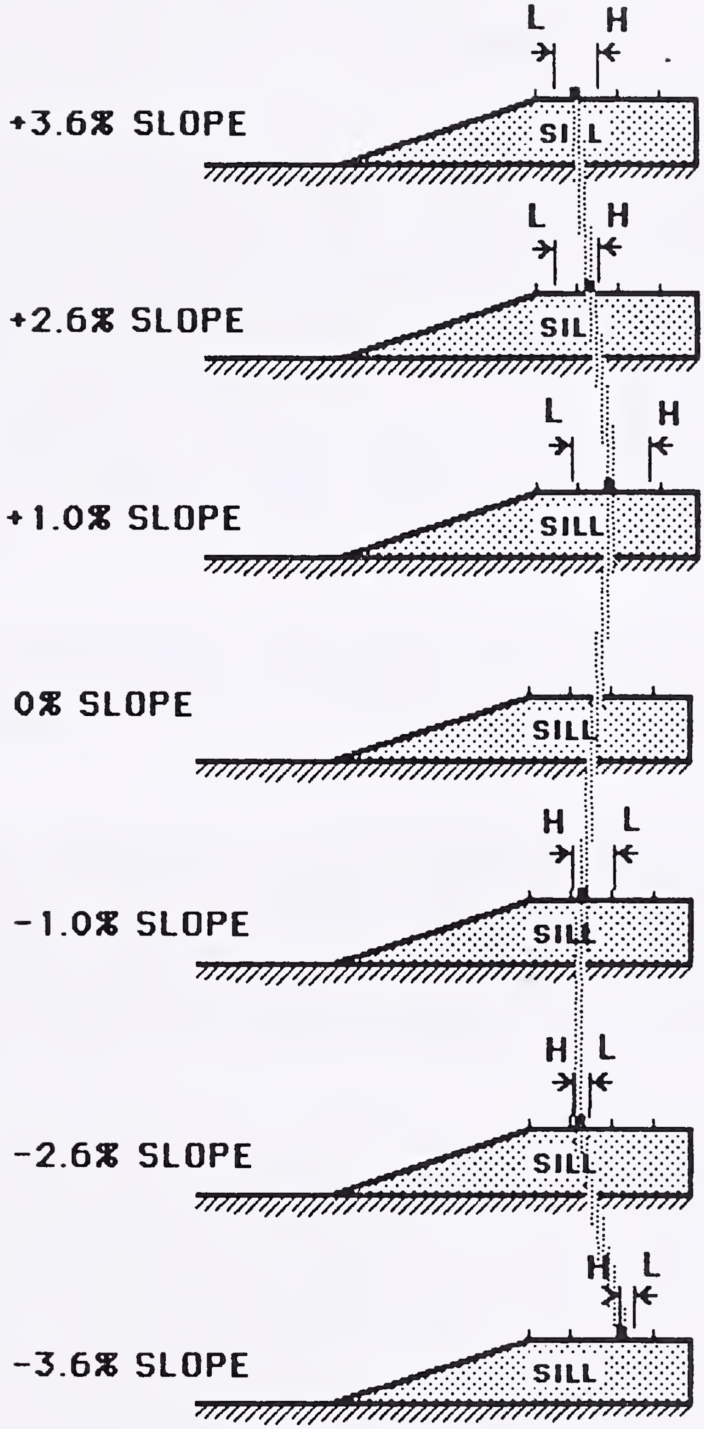


Figure 8: Relative locations of control section for high flow rates (H) and for low flow rate (L) for various slopes. The most usual apparent location of the control section is indicated by the black square dot.

TITLE: SURFACE WATER DRAINAGE FROM LEVEL FURROWS

NRP: 20740 CRIS WORK UNIT: 5422-20740-004

INTRODUCTION:

Level-basin irrigation involves applying water to a level ground area of any shape, which is surrounded by a dike or other control barrier. Inherently, irrigations on basins are uniform and efficient when the basin system has been properly designed and leveled and the soil is uniform throughout the basin. Traditionally, basins are irrigated by turning a desired water volume into the basin where it is confined until infiltrated. By configuring the supply channel properly in relation to the basin surface, water can be drained from the basin to effect lighter applications per irrigation. In many instances light applications are desirable to maintain high efficiencies (limited water holding capacity of sandy soils) and optimum soil, water, and air conditions for plant growth (low final intake rates on heavy clay soils can cause serious aeration problems).

The purpose of the project is to quantify the surface drainage phenomenon by a series of field studies. The studies will provide a data base for hydraulic modeling verification and guidelines for designing and managing such systems.

FIELD OPERATION:

The main difference between the surface-drained level basins and conventional level basins is the way in which the water is conveyed and distributed to the basins. With conventional level basins, the water is turned into the basins from a canal or pipeline controlled with gates. With row or bed crops, secondary (temporary) ditches or channels are used to spread and divert water into the furrows. Once the required volume of water is applied to a basin, the gate is closed and the irrigation is complete.

In the surface-drained level-basin system, the canal not only conveys the water to the basin but is also used to spread and divert the water directly to the basin surface. The canal can be either lined or unlined, depending on the specific requirements of the user. The system consists of a series of level basins, each irrigated separately by checking the water in the channel or canal reach bordering the basin to be irrigated, Fig. 1. The channel is used only for conveyance when the water is not checked. When not checked, the water surface is below the basin surface or bottom of the furrow, Fig. 2. The hydraulics of the water control within the channel or canal is similar to that described by Garton, et al. (1964) and Taylor, et al. (1982), where spiles (pipes through the side of the canal) and side weirs were respectively used to turn water out of the canal. The unique difference between those systems and the one described herein is that the outlet from the channel is the furrow itself. Laser-controlled leveling (Dedrick, et al., 1982) provides the precision needed to use the furrows in this manner.

The irrigation of the separate basins can proceed either in an upstream (basin 4 to basin 1, Fig. 1) or downstream (basin 1 to basin 4) direc-

tion. If upstream, then the water applied to a basin remains on the basin until infiltrated. This is similar to the traditional way in which basins are irrigated in that all water introduced to a basin stays in that basin. If, however, the irrigation progresses in a downstream direction, some of the water applied is drained back into the supply canal when the irrigation is changed to a lower-lying basin. This results in net irrigation application depths that are less (by the amount drained from the basin or furrow) than when done in the conventional manner. For more detail, see Dedrick (1983) and Dedrick (1984).

EVALUATION OF AN ACTUAL SURFACE DRAINING SYSTEM:

In September 1983, an irrigation was evaluated on a farm where the surface water drainage scheme was being used. Water surface elevations, shown in Fig. 2, were actual elevations measured while irrigating a basin. Specific field statistics and measurements made were:

Basin Size: length 180 m (590 ft), width 150 m (490 ft), area 2.7 ha (6.6 acres)
Crop: Potatoes
Number of Furrows: 173
Row Spacing: 86 cm (34 in)
Irrigation Time (Time between when water first entered the furrows and when the check gate was opened): 36 min.
Flow Rate: 650 L/s (23 ft^3/s)
Flow Rate per Furrow: 3.76 L/s (0.13 ft^3/s, 60 gal/min)
Water Applied, depth (gross until cut-off): 53mm (2.1 in)
Furrow Surface: Smooth
Water Advance Time: 35-45 min depending on furrow
Maximum Furrow Depth: 21 cm (8.2 in)
Maximum Water Depth in Furrow: 15.2 cm (6 in)

Four furrows were studied in detail during the irrigation to estimate the proportion of water drained once the water was changed to a lower basin. Quantity of water infiltrated along the furrows was estimated by opportunity time and infiltration characteristics determined from blocked furrow infiltrometer studies conducted just prior to the irrigation. The volume of water in the test furrows was estimated from the furrow cross-section and the water surface readings taken at various locations along the furrow throughout the irrigation. The volume of water drained from the furrows was determined by the difference between the volume stored in the furrows at the time of change and the infiltrated water from the time of change until recession was complete. The average volume of water in the four furrows ranged from 4.25 to 4.80 m^3 which was equivalent to water depths of 27.5 and 31 mm. The portion that infiltrated ranged from 2.40 to 2.85 m^3. Thus, by subtraction, between 40 and 45 percent of the water in the furrow at the time of change drained back into the supply channel.

Looking at two furrows in more detail, Fig. 3, the amount of water stored in a furrow at the time of switch, ranged from nearly 40 mm equivalent depth at the inlet of the furrow to about one-half that amount at the far end of the furrow. As expected, the amount of water

drained from the furrows decreased with distance from the inlet, ranging from about 70% at the inlet to about 30 to 50% at the far end of the furrow. The equivalent depth of water drained was 12 and 13 mm for the two furrows. For these individual furrows, the net depth applied was about 40 or 41 mm (53 mm [gross applied] less amount drained), which is about 25% less than if the drainage had not occurred.

The exact proportion of water going to infiltration and drainage will depend on the intake characteristics of the soil, length and cross-section of the furrow, volume and distribution of water in the furrow at the time of cutoff, and surface roughness. The information presented in Fig. 3 illustrates only the surface drainage aspect of this irrigation scheme which can lead to light applications. As with any irrigation method, light applications must be uniformly applied. Management guidelines will need to be perfected to assure the desired uniformity of application for specific field conditions. Eventually, the entire irrigation, both inflow and outflow, will be modeled.

ADDITIONAL STUDIES:

Equipment has been developed to more accurately study the irrigation/drainage process for level furrows. The key difference in these studies and those reported in the previous section is that the inflow and outflow are recorded for individual furrows.

The inflow to each furrow can be regulated to a desired flow rate by the use of an inlet box consisting of a globe valve, stilling baffle, and small modified broad-crested weir (Clemmens, et al., 1984). A submersible pump is used to supply the water to each inlet box and furrow. By carefully measuring inflow and holding it constant, a volume-balance can be performed as the water advances along the furrow. This information can then be used to develop an intake function for the furrow directly rather than inferring it from infiltrometer studies.

A specially designed portable broad-crested weir was constructed to measure the water as it drains out of the furrow. Measuring drainage directly provides a volume balance check on the furrow during the drainage stage. The flume used to measure the drainage was designed to approximate the furrow cross-section so that the flume was nonrestricting to the drainage process, e.g., outlet of furrow free-draining.

Water depth along the furrows is recorded automatically by adapting the bubbler/pressure transducer system reported by Dedrick and Clemmens (1984) and Clemmens and Dedrick (1984). Bubblers are located at selected stations along the furrow (furrow inlet, 5, 10, 20, 30 m, and at every 30 m thereafter) to adequately define the water surface profile during a test. Compressed air, at about 70 kPa (10 psi), is supplied by an air tube common to all bubblers, Fig. 4. Air flow rate to each bubbler is controlled to about three to five bubbles per second by a flow control valve. A sensor tube was teed to the bubbler tube near the flow control valve. The sensor tube leads back to a data logging center located at the end of the furrow. Data logging was accomplished by using an expanded version of the HP41CV controlled system described by

Clemmens and Dedrick (1984). Three stations of a 24-station scanning valve are used to calibrate the pressure transducer. The other stations are used to sense the furrow bubblers via the sensor tubes. The stations are repeatedly scanned, taking about five seconds per station, with the transducer voltages recorded on a cassette tape.

The furrow bubblers are mounted permanently in furrow stilling well assemblies (cups constructed from 7.5 cm [3 in] diameter PVC pipe capped on one end.) The bubblers are constructed of copper tubing. The bubbler/stilling well assembly is buried slightly below the furrow bottom at the various sites to be sensed along the furrow. Plastic tubing is used from the flow control valve to the copper tubing. Water depth in the furrow is calculated from the head sensed by the HP41CV system in conjunction with field-surveying the furrow bottom and top of the buried stilling well.

Equipment has been developed to study three furrows simultaneously. The equipment is adaptable to any furrow evaluation, e.g., draining or not draining, surge, etc.

RESULTS:

The equipment and field procedures for studying surface drainage from a level furrow were developed during 1984. A field crew of three or four persons is needed to prepare and conduct tests on a set of three furrows. Data reduction programs are being developed to provide infiltration functions, water surface profiles, advance, recession, water drained from the furrow, distribution of the amount drained along the furrow, and final irrigation uniformities.

Twelve level furrows, 180 m long, were studied at the Maricopa Agricultural Center during 1984. The tests were used mainly to develop field procedures. A series of tests on three furrows should provide useful data for future analysis. These data have not been analyzed for inclusion in this report.

The bubbler/pressure transducer concept for sensing water depth along the furrows has application whenever multiple water level recordings are needed. Two additional applications being used here at the U. S. Water Conservation Laboratory include monitoring open channel water delivery systems and ring infiltrometers.

SUMMARY AND CONCLUSIONS:

A project has been initiated to study surface drainage of level furrows immediately following an irrigation (water advance). The main purposes of the study are to quantify this surface drainage phenomenon by providing a data base for hydraulic modeling verification and guidelines for design and management.

An operational surface-draining level-furrow system was studied in 1983. In an evaluation of the system as it was operating in the field, about 12 mm (equivalent depth related to 86cm [34 in] row width) of a gross 53

mm water applied was drained back out of the furrows. This amounted to a net application nearly 25% less than if no drainage had occurred. The relative amount of drainage will, however, depend on many factors such as intake, furrow length, furrow cross-section, and water volume and its distribution in the furrow at the time drainage starts.

Equipment has been developed to accurately evaluate furrows on an individual basis. Inflow to each furrow is accurately regulated, and drainage from the furrow is measured. Both measurements are made with portable broad-crested weirs. Water surface profiles throughout a furrow are developed from a data logging scheme using an HP41CV controlled bubbler system. Preliminary studies have been completed on a few furrows.

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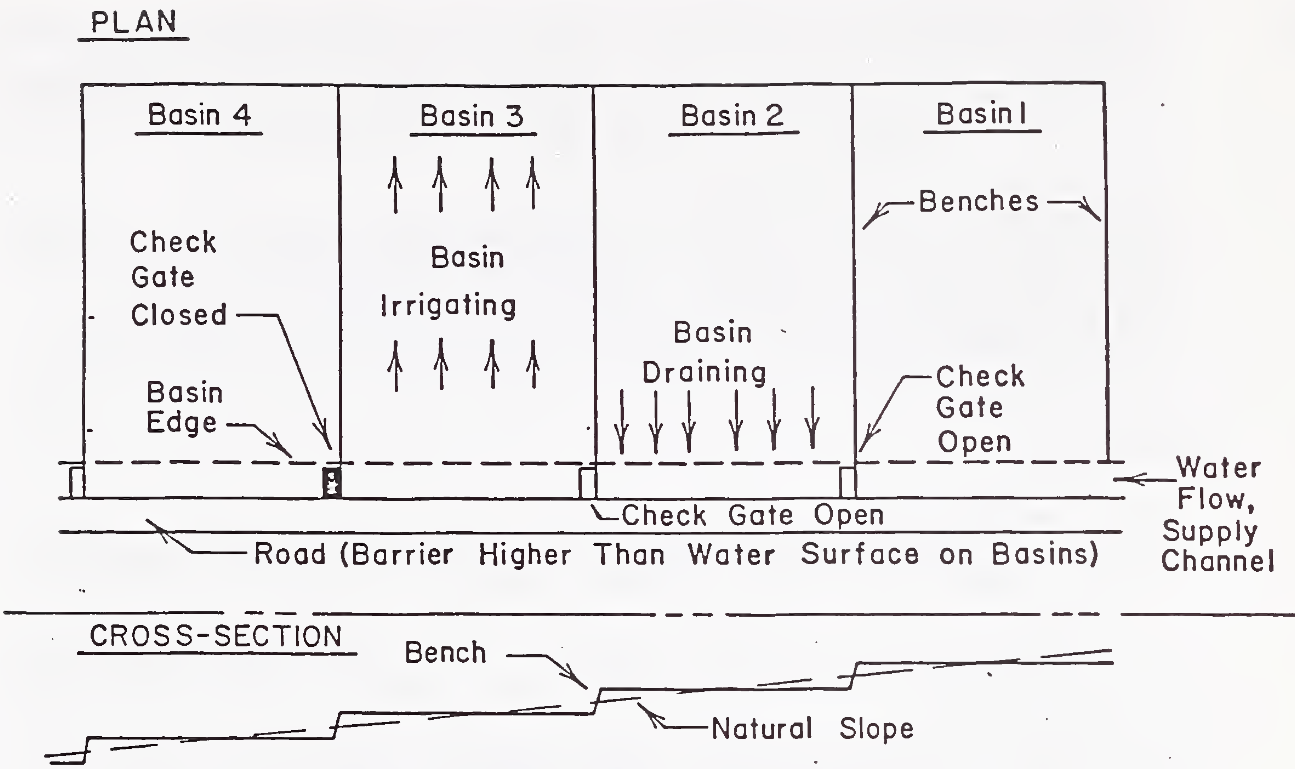

Fig. 1. Plan and cross-sectional views of level basins (benched) irrigated from an unlined channel. The irrigation has just been changed from basin 2 to basin 3 (downstream).

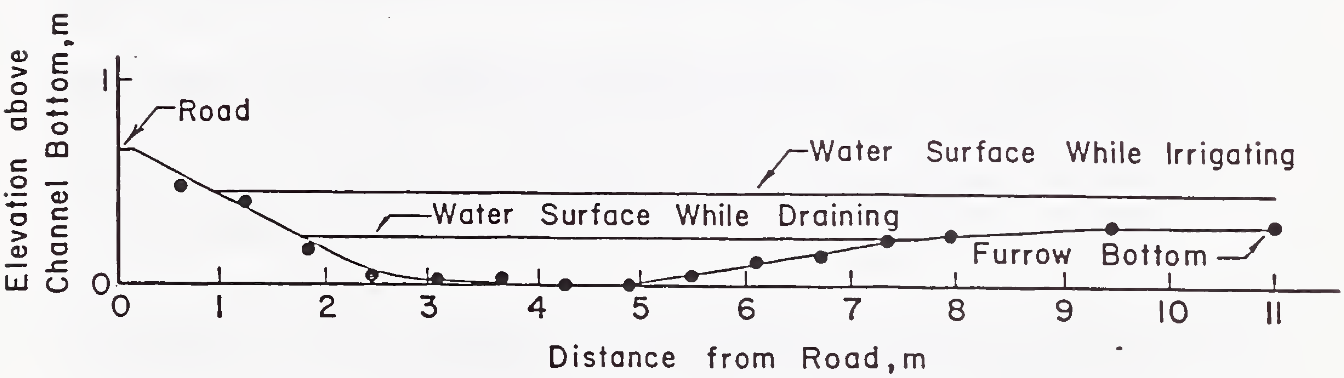

Fig. 2. Cross-sectional view of unlined supply channel from field road to level basin. Water surfaces shown were those recorded during an irrigation with the maximum depth reaching about 15 cm (6 in). Note that the vertical and horizontal scales are not the same.

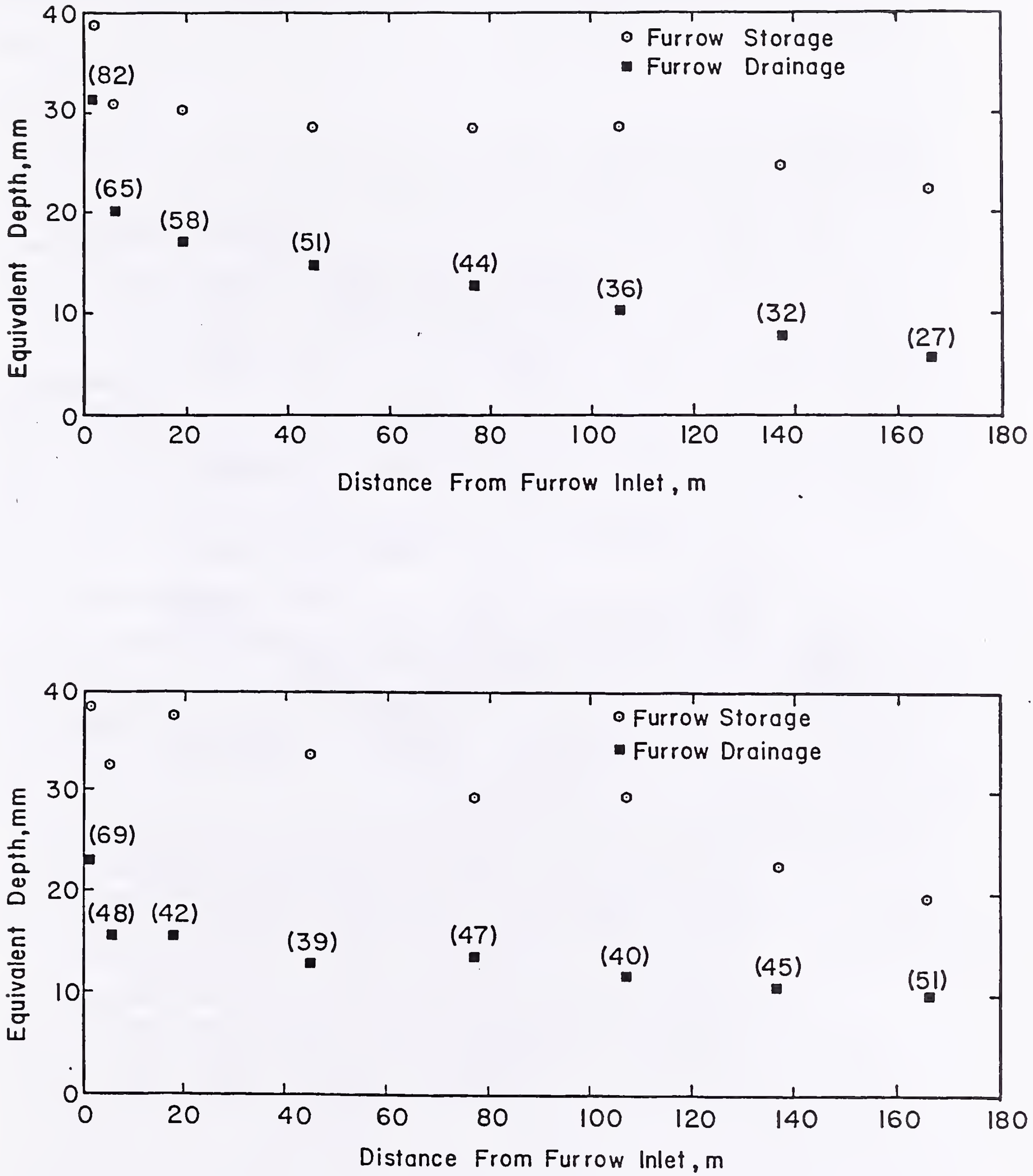

Fig. 3. Amount of water stored in two furrows at the time the irrigation was changed to a lower-lying basin and the portion subsequently drained (runoff) from the furrows. The percent drained is represented by the numbers in parentheses. Equivalent depths are based on 86 cm (34 in) row spacing.

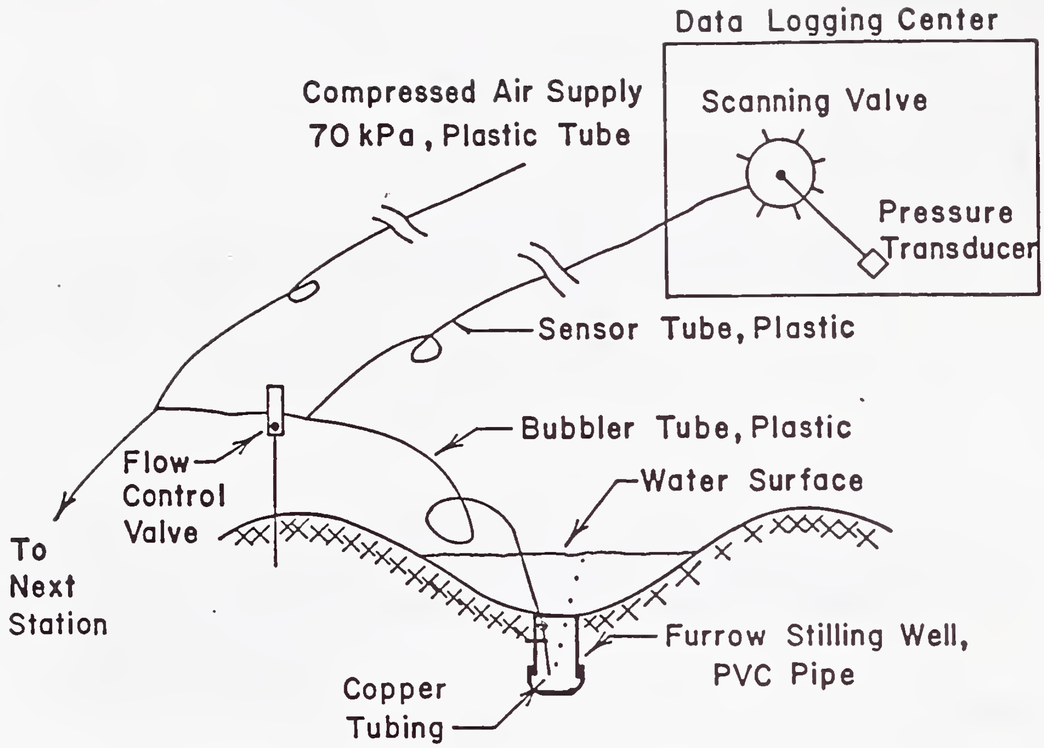

Fig. 4. Sketch of the water depth sensing scheme used to experimentally define the water surface profile along a furrow. A bubbler and stilling well assembly is installed at each location within a furrow where a near continuous record of the water depth is required. Although not shown, other sensor tubes from other stations along the furrow would be hooked to the scanning valve. The stations are repeatedly scanned with the corresponding voltage output from the pressure transducer being stored on a cassette. The system is controlled by an HP41CV.

TITLE: IRRIGATION WATER MANAGEMENT FOR GUAR SEED PRODUCTION

NRP: 20740 CRIS WORK UNIT: 5510-20740-003

INTRODUCTION:

Particularly in some parts of the Southwest, the rapidly growing urban areas demand an increasing proportion of an inadequate water supply and are able to pay more for it than are agricultural users, even to the point of buying agricultural land just to acquire the water rights. The development of new agricultural crops with low water requirements, tolerance to drought, or the capacity to complete their life cycles quickly when adequate moisture is available has the potential for maintaining agriculture where water supplies are decreasing. Within the past two years, land areas have been planted to guar for seed production in Texas and Arizona. The need for irrigation water management research on guar seed production was discussed in the 1983 annual report along with a review of literature. The objectives of the 1983-84 experiments were: (1) to determine the estimated evapotranspiration requirement for guar seed production; and (2) to determine plant growth and yield relations for guar seed production with respect to varieties, plant populations, and irrigation treatments.

Field Procedures:

The 1984 study was conducted at the new Maricopa Agricultural Center, University of Arizona, near Maricopa, AZ. The experimental design was a completely randomized, split, split plot design (Figure 1) with four replicates of six irrigation treatments as main plots, three cultivars as subplots, and three plant populations as sub-subplots. The irrigation treatments (Table 1) were based on plant growth stages as follows: I_1 - three irrigations, 20, 60, and 80 days after establishment; I_2 - two irrigations, 35 and 60 days after establishment; I_3 - three irrigations, 35, 60, and 80 days after establishment; I_4 - three irrigations, 20, 35, 80 days after establishment; I_5 - three irrigations, 20, 35, and 60 days after establishment; and I_6 - four irrigations, 20, 35, 60 and 80 days after establishment. Flowering was estimated at about 30 - 40 days after planting, and pod filling at about 60 - 90 days after planting.

The three cultivars were selected by Dennis Ray, Plant Breeder, University of Arizona, as the most promising of different breeding types for guar seed production. Kinman (C_1) is being commercially planted for both vegetative and reproductive growth. The C_1 cultivar has moderate branching throughout the height of the plant and full season maturity. T_x 78-3695 (C_2) is a sparse branching, indeterminate cultivar with full-season maturity, selected for seed production in Arizona and Texas. The plant leaves are glaberous (non-pubescent) with a waxy cuticle. T_x 79-2741 (C_3) is a basal branching, determinate cultivar with raceme initiation at each node and medium maturity. The C_3 cultivar was an F-2 selection developed cooperatively by the Agriculture Research Service, Texas Agriculture Experiment Station, and the Arizona Agricultural Experiment Station. At higher elevations, T_x 78-3695 has been reported to outyield Kinman and T_x 79-2741.

The three plant populations were based on two rows placed on a conventional bed, 1 m (40 in) on center, with spacings along the row of 2.54 cm (1 in), 7.62 cm (3 in), and 15.24 cm (6 inches) for populations of 775,900 plants/ha, (314,000 plants/ac), 259,500 plants/ha, (105,000 plants/ac), and 128,000 plants/ha (52,000 plants/ac), (P_1, P_2, and P_3), respectively.

Before planting, the field was plowed, leveled, applied with trifluralin (a, a, a-Trifluoro-2,6 dinitro-N, N-dipropyl-p-toluidine or Treflan[1/]) herbicide at 0.84 kg/ha (0.75 lbs/ac) for weed control, and standard beds constructed No preplant irrigations or fertilizer applications were given. Guar was planted on June 15 with a precision, belt planter to the highest plant population. Three irrigations were applied over a one-week period from June 15 to 22 for germination and plant establishment. The field was cultivated thereafter, and two applications of MSMA (monosodium methanearsonate or Weed-E-Rad)[1/] herbicide were given for weed control. The plots were then thinned to the three plant populations in early July, and differential irrigations started on July 13. Water applications were measured by a propeller-type water meter, and aluminum gated pipe was used to deliver the water to the individual plots surrounded by earthen border dikes. The irrigation water contained about 1.1 dS/m (690 ppm) of total dissolved salts.

Volumetric water contents were determined by neutron moisture meters with 18 neutron access tubes located in the C_1 (Kinman) cultivar and medium P_2 (259,500 plants/ha) population, to a 1.8-m (6 ft) soil depth. Field capacity for the medium water-holding capacity Mohall sandy loam soil (Typic Haplargid, fine-loamy, mixed, hyperthermic) was estimated at 25.0% by volume, whereas wilting point was estimated at about 15.0% for 1983. The neutron meters were field calibrated at the site, and consumptive water use or estimated evapotranspiration was calculated from the soil water depletions to a 1.8 m (6 ft) depth. Deep percolation losses were assumed to be minimal for the deep-rooted guar crop. Meteorological factors affecting plant water use were monitored by a portable weather station equipped with a micrologger. The weather data was measured on the I_3 irrigation treatment and included solar radiation and wind speed at a 2-m (6.6 ft) height; net radiation, air temperature, and relative humidity, at the 1.5-m (4.9 ft) height; and soil temperature at the 1-cm (0.8 in) depth.

Prior to harvesting the guar in late November, three plants per sub-plot or irrigation-cultivar-population treatment in all three replicates were sampled at maturity to determine the number of pods/plant, number of seeds/pod, and dry weight/plant. Harvest areas of 61 m (20 ft) x 2.0 m (6.7 ft, two beds wide) were established by removal of adjacent plant rows. The plants were mowed in the morning when moisture was on the pods, and were threshed in the afternoon when the material was dry. This procedure minimized shattering losses.

1/ Trade names and company names are included for the benefit of reader and do not imply any endorsement or preferential treatment of the product listed by either the authors or the US Department of Agriculture.

RESULTS AND DISCUSSION:

Three irrigations were given by gravity flow (siphon tubes) for germination and establishment for an approximate total of 200 mm (8 in). This amount was required within a one week period for adequate germination of the C_2(T_x 78-3695) and C_3(T_x 79-2741) cultivars. There was a high population of groundcherry (Physalis wrightii Gray). To overcome this problem, the two applications of MSMA were given. Although recommended for groundcherry elimination, some reduction in the overall growth and yield of guar can be expected (Hamilton 1983).

Table 2 lists the amounts of water applied and calculated seasonal consumptive use or soil water depletion for the six irrigation treatments. After applying approximately 200 mm (8 in) for establishment, the water applications by irrigation treatment were as follows: I_1, received three irrigations (July 13, August 24, and September 14) totaling 300 mm (12.0 in); I_2 received two irrigations (July 27 and August 24) totaling 200 mm (8.0 in); I_3 received three irrigations (July 27, August 24 and September 14) totaling 300 mm (12.0 in); I_4 received three irrigations (July 13, July 27 and September 14) totaling 300 mm (12.0 in); I_5 received three irrigations (July 13, July 27 and August 24) totaling 300 mm (12.0 in); and I_6 received four irrigations (July 13, July 27, August 24 and September 14) totaling 400 mm (16.0 in).

The calculated seasonal consumptive water use (Table 2) and peak water use in early August for the respective irrigation treatments were as follows: I_1 was 475 mm (16.4 in) with 5 mm (0.2 in)/day; I_2 was 460 mm (18.1 in) with 6.25 mm (.25 in)/day; I_3 was 480 mm (18.8 in) with 6.3 mm (.25 in)/day; I_4 was 510 mm (20.1 in) with 8.25 mm (0.32 in)/day; I_5 was 550 mm (21.8 in) with 8.5 mm (0.33 in)/day; and I_6 was 440 mm (17.2 in) with 5.75 mm (0.23 in)/day. Indications from the 1984 season are that the consumptive water use is less for guar seed production, regardless of the irrigation treatment, than for forage production with a reported seasonal use of 587 mm (23.1 in) and a peak use rate of 7 mm (0.28 in)/day (Erie et al. 1982). However, all the soil water content measurements were taken on the C_1 (Kinman) cultivar and the medium P_2 (259,500 plants/ha) population which could have lower water use than the other two cultivars (T_x 38-3695, C_2, T_x 79-2741, C_3) that had larger dry weights. Seasonal consumptive water use curves for the two highest seed yielding I_1 and I_3 irrigation treatments are shown in Figures 2 and 3.

Mean seed yields for the six irrigation treatments, three cultivars, and three plant populations are listed in Table 3. The highest seed production amounting to 2096 kg/ha (1870 lbs/ac) occurred on the I_6 irrigation treatment (four irrigations), the C_3 (T_x 79-2741) cultivar, and the P_1 (775,900 plants/ha) population. Generally, the higher plant populations of the C_3 (T_x 79-2741) cultivar produce more seed yield. This cultivar has very little lateral branching with most reproductive growth occuring on the main stem; in this case the plant needs only enough space for the main stem, and it is assumed that higher spacing for this cultivar can amount to high yields, whereas the low populations do not yield as high because the inter-plant space is unused. The P_1 (775,900 plants/ha) and P_2 (259,500 plants/ha) populations of C_3 (T_x 79-2741) have a signifi-

cantly higher yield than the P_3 (128,000 plants/ha) population. For the C_1 (Kinman) cultivar, which has high lateral branching throughout the plant, the high population (P_1) tends to decrease yield as the plants become crowded, and the lower populations (P_2 and P_3) tend to favor higher yields as the plant has room for branching. For this cultivar P_2 (259,500 plants /ha) and P_3 (128,000 plants/ha) have a significantly higher yield than P_1 (775,900 plants/ha). For the C_2 (T_x 78-3695) cultivar, with medium branching, Plant population had no significant effect on yield. Under irrigated agriculture in central Arizona, C_3 (T_x 79-2741) has a significantly higher 11% yield increases over C_2 (T_x 78-3695); and C_2 (T_x 78-3695) had a significantly higher 12% yield increase over C_1 (Kinman) under the same set of given conditions.

The I_1 treatment (three, critical irrigations) had the highest overall seed yields, whereas the I_2 treatment (two, mid-season irrigations) obtained the lowest yields. The increase in seed production for the I_1 compared with I_2 treatment amounted to 17%. The I_1 treatment (mean seed yield of 1700 kg/ha) was a result of irrigations 20 days after establishment (during root development), 60 days after establishment (during flowering and initial pod development) and 80 days after establishment (during mid-pod filling). The I_2 treatment (mean seed yield of 1451 kg/ha) with an irrigation 35 days following germination (during flowering only) and 60 days may have stressed the guar plant somewhat during pod filling to result in the lowest overall yields. The I_3 treatment (mean seed yield of 1580 kg/ha) with three irrigations during the season (35, 60, and 80 days after establishment) produced slightly lower seed yields than the I_1 treatment suggesting that an irrigation was needed before flower initiation; however, the 8% yield reduction was not significant at the 5% level. The I_4 treatment (mean seed yield of 1499 kg/ha) with three irrigations (20, 35, and 80 days after establishment) resulted in the second lowest production indicating that a longer water stress period was required early, that the 35th day irrigation (during flowering) was less important than the 20th day irrigation (before flowering), and that a late season irrigation was necessary (during mid-pod filling). The I_5 treatment (mean seed yield of 1564 kg/ha) with three irrigations (20, 35 and 60 days) produced nearly the same yield as the I_4 treatment supporting the concept that an early plant water stress period was advantageous. The I_6 treatment (mean seed yields of 1693 kg/ha) with four post-establishment irrigations (20, 35, 60, and 80 days) attained as high a yield as I_1 but with excessive vegetative growth. The water use efficiency (seed production per unit of water use) was lower for the I_6 than the I_1 and I_3 treatments. The I_6 treatments indicate that a fourth irrigation is unnecessary under most field conditions.

Size or weight per 500 seeds was primarily a function of irrigation treatment rather than plant population or cultivar. Varying plant populations had little affect on seed size; however, the higher yielding C_3 (T_x 79-2741) cultivar had a slightly smaller seed size than the C_1 (Kinman) or C_2 (T_x 78-3695) cultivars. The optimum I_1 and I_3 irrigation treatments as well as the I_6 treatment had a larger seed size than the other treatments.

Reproductive growth (seed plus pod weight) was generally higher for the higher yielding irrigation treatments, with the C_3 (T_x 79-2741) cultivar exhibiting the highest reproductive growth averages. The effect of population is a tendency for overall growth (both reproductive and vegetative) to be higher with the low plant population. Vegetative growth (leaves, branches, and roots) was more on the C_2 (T_x 78-3695) than the C_3 (T_x 79-2741) and C_1 (Kinman) cultivars as listed in Table 6. Both reproductive and vegetative growth stayed nearly constant for the C_2 and C_3 cultivars within the various irrigation treatments and plant populations; whereas, the C_1 cultivar had reduced growth for the higher P_1 (775,900 plants/ha) compared with the P_2 (259,500 plants/ha) and P_3 (128,000 plants/ha) plant populations. The higher seed yield for the C_3 over C_2 and C_1 cultivars was again because of a greater number of pods/plant. The guar pods on the C_3 (T_x 79-2741) cultivar occurred mainly on the main stem compared with the pods being more dispersed on the lateral branches for the other two cultivars.

SUMMARY AND CONCLUSIONS:

Guar for seed production has the potential of being an economical crop for the semiarid Southwest as well as a low water use crop. Current prices of guar seed have been depressed; however, future markets will depend largely on an increased demand for guar gum as a drilling fluid additive in the oil-well drilling industry. The highest yields resulted from the T_x 79-2741 cultivar (soon to be released as Lewis), the high plant population of 775,900 plants/ha, and three or four key irrigations after establishments. This new cultivar should increase guar seed production by nearly 25 percent over older varieties. Proper timing of irrigations is extremely important since only three, small gravity irrigations are needed, and late watering or a fourth irrigation can lead to delayed maturity. The three irrigations are as follows: one before flowering, followed by another during flowering and initial pod development, and one at about mid-pod filling. Consumptive water use on the optimum treatment was about 380 mm in 1983 and 415 mm in 1984 for seed production, which was considerably less than the previously reported seasonal use of about 590 mm for guar forage production in central Arizona.

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Table 1. Six irrigation treatments used for guar seed production at the Maricopa Agricultural Center, Maricopa, Arizona, 1984.

Days after Establishment 1/	Irrigation Treatment 2/					
	I_1	I_2	I_3	I_4	I_5	I_6
20 Days (Jul 13)	X			X	X	X
35 Days (Jul 27) 3/		X	X	X	X	X
60 Days (Aug 24) 4/	X	X	X		X	X
80 Days (Sep 14)	X		X	X		X

1/ Plots considered established on July 5 (planted on June 18) with plant heights of 100 mm.

2/ Each irrigation about 100 mm of water

3/ Flowering estimated at about 30-40 days after establishment

4/ Pod filling estimated at about 60-90 days after establishment

Table 2. Total water applications and calculated seasonal consumptive water use for the six irrigation treatments used for guar seed production at the Maricopa Agricultural Center, Maricopa, Arizona, 1984.

Irrigation Treatment 1/	Total Water Applied 2/	Seasonal Consumptive Water Use
	(mm)	(mm)
I_1	500	415
I_2	400	460
I_3	500	480
I_4	500	510
I_5	500	550
I_6	600	440

1/ Irrigation treatments described in Table 1.

2/ Includes 200 mm of water for establishment.

Table 3. Guar seed production for six irrigation treatments, three cultivars, and three plant populations at Maricopa, Arizona, 1984.

Irrigation Treatment 1/	C_1 Cultivar 2/			C_2 Cultivar			C_3 Cultivar			Irrigation Treatment Mean
	P_1	P_2	P_3 3/	P_1	P_2	P_3	P_1	P_2	P_3	
				Seed Yields in Kg/ha						
I_1	1531	1547	1531	1862	1846	1693	1846	1757	1693	1700 a*
I_2	1177	1394	1314	1354	1322	1435	1636	1717	1685	1451 c
I_3	1394	1330	1370	1644	1548	1548	1822	1757	1870	1580 abc
I_4	1306	1378	1290	1644	1636	1548	1467	1757	1435	1499 bc
I_5	1402	1499	1451	1491	1547	1475	1709	1830	1685	1564 abc
I_6	1394	1564	1572	1507	1709	1604	2096	1902	1870	1693 ab
Plant Population Means	1798	1759	1613	1766	1791	1614	1935	1946	1852	
Cultivar Means		1411 c			1580 b			1749 a*		

1/ Irrigation treatments described in Table 1.

2/ C_1 = Kinman, C_2 = T_x 78-3695, C_3 = T_x 79-2741.

3/ P_1 = 775,900 plants/ha, P_2 = 259,500 plants/ha, and P_3 = 128,000 plants/ha.

* Statistical significance .05 (Duncan's New Multiple Range Test) a,b, etc.

Table 4. Guar seed weights for six irrigation treatments, three cultivars, and three plant populations at Maricopa, Arizona, 1984.

Irrigation Treatment 1/	C_1 Cultivar 2/			C_2 Cultivar			C_3 Cultivar			Irrigation Treatment Mean
	P_1	P_2	P_3 3/	P_1	P_2	P_3	P_1	P_2	P_3	
				Seed Weights in g/500 seeds						
I_1	15.3	14.5	15.1	16.3	14.2	15.3	16.3	15.7	14.6	15.3
I_2	16.6	13.9	15.5	15.3	15	15.4	13	13.8	14.9	14.8
I_3	15.7	15.4	15.5	15	13.9	16.2	15.2	13.5	14.8	15
I_4	15.3	14.6	13.9	13.6	14.8	15.3	13.6	14.8	12.4	14.3
I_5	14.4	17.6	14	14.6	14.2	13.8	12.9	13.1	15.2	14.4
I_6	14.9	15.4	16.1	14.3	14.6	15.4	16.1	13.3	14.7	15
Plant Population Means	15.4	15.2	15	14.8	14.5	15.2	14.5	14	14.4	
Cultivar Means		15.2			14.8			14.3		

1/ Irrigation treatments described in Table 1.

2/ C_1 = Kinman, C_2 = T_x 78-3695, C_3 = T_x 79-2741.

3/ P_1 = 775,900 plants/ha, P_2 = 257,500 plants/ha, and P_3 = 128,000 plants/ha.

Table 5. Guar reproductive dry weights for six irrigation treatments, three cultivars, and three plant populations at Maricopa, Arizona, 1984.

Irrigation Treatment 1/	C_1 Cultivar 2/			C_2 Cultivar			C_3 Cultivar			Irrigation Treatment Mean
	P_1	P_2	P_3 3/	P_1	P_2	P_3	P_1	P_2	P_3	
				Seed and pod dry weights in g/3 plants						
I_1	40.9	101.9	92.3	61.7	87.2	226.3	124.4	168.8	173.8	119.7
I_2	57.8	83.9	77.4	65.4	123.9	101.2	94.7	145.4	223.8	108.1
I_3	78.8	72.5	129	87.4	105.2	191.6	105.1	194.1	202.9	129.6
I_4	56.8	65.8	104.5	122.2	125	66	57.9	87.5	165.9	94.7
I_5	51.5	84.6	119.9	109.4	132.6	104.7	72.5	150	187.1	112.5
I_6	57	78.7	74.9	141.9	97	193.7	60	81.5	175.4	106.7
Plant Population Mean	57.1	81.2	99.7	98	111.8	147.3	85.8	199.1	188.2	
Cultivar Means		79.3			119			157.7		

1/ Irrigation treatments described in Table 1.

2/ C_1 = Kinman, C_2 = T_x 78-3695, C_3 = T_x 79-2741.

3/ P_1 = 775,900 plants/ha, P_2 = 259,500 plants/ha, and P_3 = 128,000 plants/ha.

Table 6. Guar vegetative dry weights for six irrigation treatments, three cultivars, and three plant populations at Maricopa, Arizona, 1984.

Irrigation Treatment 1/	C_1 Cultivar 2/			C_2 Cultivar			C_3 Cultivar			Irrigation Treatment Mean
	P_1	P_2	P_3 3/	P_1	P_2	P_3	P_1	P_2	P_3	
					Branches, stems, and leaves in g/3 plants					
I_1	36.9	54.6	66.8	58.8	81.1	169.3	54.6	78.4	50.4	72.3
I_2	60.4	68.3	83.1	48.2	86.9	68.6	49.0	76.1	100.6	71.3
I_3	63.5	61.6	101.5	79.5	97.8	78.5	62.1	90.4	88.8	39.1
I_4	34.2	52.6	58	104	90.1	51.6	36.2	37.5	123.1	40.2
I_5	55.7	84.7	95.5	97.8	102.6	57.6	46.7	84.5	85.1	78.9
I_6	57	88	101.8	102.2	77	153.6	42.1	41.9	88.4	83.5
Plant Population Means	51.3	68.3	84.4	81.8	89.4	96.5	48.6	68.2	89.4	
Cultivar Means		68			89.2			68.7		

1/ Irrigation treatments described in Table 1.

2/ C_1 = Kinman, C_2 = T_x 78-3695, C_3 = T_x 79-2741.

3/ P_1 = 775,900 plants/ha, P_2 = 259,500 plants/ha, and P_3 = 128,000 plants/ha.

1984 GUAR EXPERIMENT
MARICOPA AGRICULTURAL CENTER

	P_2C_1	I_4 P_3C_1	P_2C_1	P_3C_2	I_2 P_1C_2	P_3C_2	P_2C_3	I_1 P_1C_3	P_3C_3	P_1C_3	I_6 P_2C_3	P_3C_3	P_2C_3	I_5 P_3C_3	P_1C_3	P_1C_3	I_3 P_2C_3	P_3C_3
REP 1	P_2C_3	P_3C_3	P_2C_3	P_3C_1	P_1C_1	P_3C_1	P_2C_1	P_1C_1	P_3C_1	P_1C_1	P_2C_1	P_3C_1	P_2C_1	P_3C_1	P_1C_1	P_1C_2	P_2C_2	P_3C_2
	P_2C_2	P_3C_2	P_2C_2	P_3C_3	P_1C_3	P_3C_3	P_2C_2	P_1C_2	P_3C_2	P_1C_2	P_2C_2	P_3C_2	P_2C_2	P_3C_2	P_1C_2	P_1C_1	P_2C_1	P_3C_1
	P_1C_2	I_5 P_3C_2	P_1C_2	P_3C_1	I_6 P_1C_1	P_2C_1	P_3C_2	I_1 P_1C_2	P_3C_2	P_3C_2	I_3 P_1C_2	P_2C_2	P_3C_2	I_4 P_1C_2	P_3C_2	P_1C_3	I_2 P_3C_3	P_2C_3
REP 2	P_1C_3	P_3C_3	P_1C_3	P_3C_3	P_1C_3	P_2C_3	P_3C_1	P_1C_1	P_3C_1	P_3C_1	P_1C_1	P_2C_1	P_3C_1	P_1C_1	P_3C_1	P_1C_1	P_3C_1	P_2C_1
	P_1C_1	P_3C_1	P_1C_1	P_3C_2	P_1C_2	P_2C_2	P_3C_3	P_1C_3	P_3C_3	P_3C_3	P_1C_3	P_2C_3	P_3C_3	P_1C_3	P_3C_3	P_1C_2	P_3C_2	P_2C_2
	P_1C_1	I_2 P_2C_1	P_3C_1	P_1C_2	I_5 P_3C_2	P_2C_2	P_2C_1	I_6 P_3C_1	P_2C_1	P_1C_3	I_3 P_2C_3	P_3C_3	P_2C_1	I_4 P_3C_1	P_1C_1	P_1C_3	I_1 P_2C_3	P_3C_3
REP 3	P_1C_2	P_2C_2	P_3C_2	P_1C_1	P_3C_1	P_2C_1	P_2C_3	P_3C_3	P_2C_3	P_1C_1	P_2C_1	P_3C_1	P_2C_3	P_3C_3	P_1C_3	P_1C_1	P_2C_1	P_3C_1
	P_1C_3	P_2C_3	P_3C_3	P_1C_3	P_3C_3	P_2C_3	P_2C_2	P_3C_2	P_2C_2	P_1C_2	P_2C_3	P_3C_2	P_2C_2	P_3C_2	P_1C_2	P_1C_2	P_2C_2	P_3C_2
	P_2C_2	I_2 P_3C_2	P_1C_2	P_3C_1	I_5 P_2C_1	P_3C_1	P_1C_3	I_3 P_2C_3	P_3C_3	P_2C_1	I_4 P_1C_1	P_3C_1	P_2C_3	I_1 P_1C_3	P_2C_3	P_2C_3	I_6 P_1C_3	P_3C_3
REP 4	P_2C_1	P_3C_1	P_1C_1	P_1C_3	P_2C_3	P_3C_3	P_1C_1	P_2C_1	P_3C_1	P_2C_3	P_1C_3	P_3C_3	P_2C_2	P_1C_2	P_2C_2	P_2C_1	P_1C_1	P_3C_1
	P_2C_3	P_2C_3	P_1C_3	P_1C_2	P_2C_2	P_3C_2	P_1C_2	P_2C_2	P_3C_2	P_2C_2	P_1C_2	P_3C_2	P_2C_1	P_1C_1	P_2C_1	P_2C_2	P_1C_2	P_3C_2

18.3m

73m

110m

LEGEND

IRRIGATION TREATMENTS

$I_1 - I_6$ SEE TABLE

CULTIVARS

C_1 = KINMAN

C_2 = SANTA CRUZ (Tx78-3695)

C_3 = LEWIS (Tx79-2741)

PLANT POPULATIONS

P_1 = 775,900 plants/HA

P_2 = 259,500 plants/HA

P_3 = 128,000 plants/HA

Figure 1. Planting diagram for guar seed production experiment at Maricopa, Arizona, 1984.

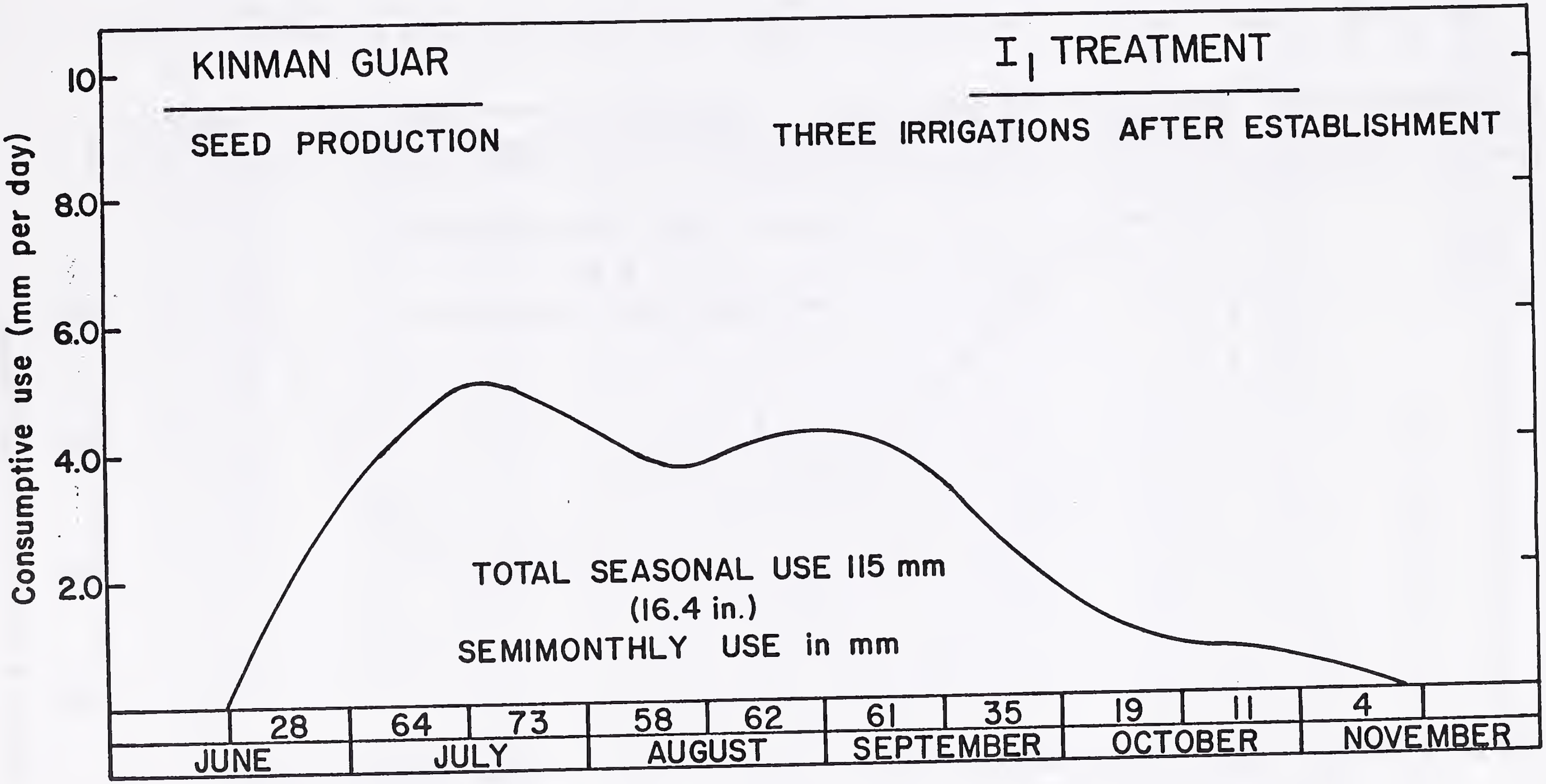

Figure 2. Consumptive water use of Kinman Guar for seed production on the I_1 irrigation treatment using the medium plant population at Maricopa, Arizona, 1984.

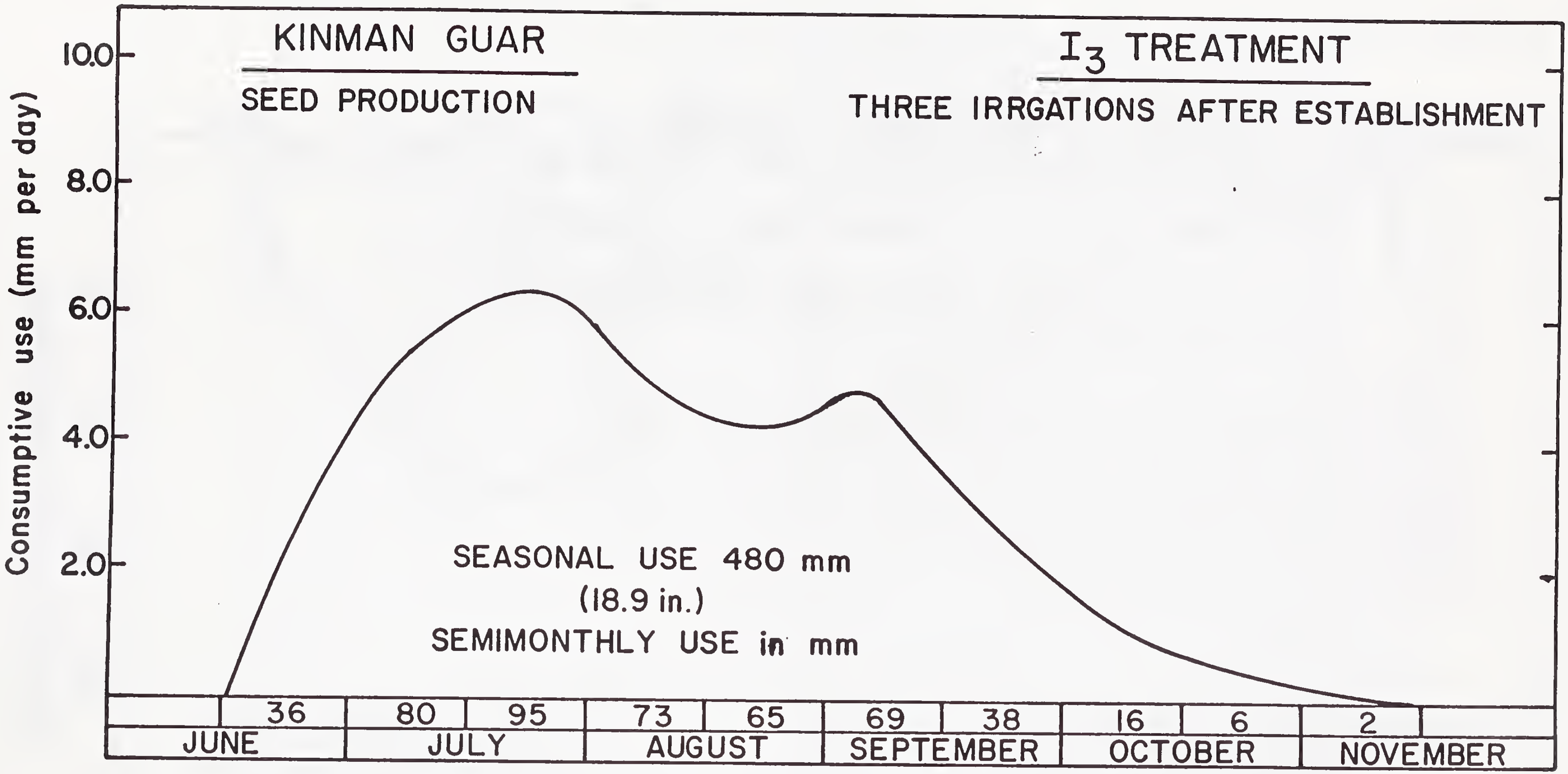

Figure 3. Consumptive water use of Kinman Guar for seed production on I_3 irrigation treatment using the medium plant population at Maricopa, Arizona, 1984.

TITLE: VARIATION IN THE MOLECULAR WEIGHT DISTRIBUTION OF RUBBER FROM CULTIVATED GUAYULE

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

The molecular weight (MW) and the molecular weight distribution (MWD) of natural rubber are directly related to rubber quality (3,6,9). Although over 2000 species of plants are capable of producing rubber, only about a dozen are recognized as producing sufficient quantites of high quality, high MW rubber necessary for commercial use (6,9). Guayule (Parthenium argentatum Gray) is capable of synthesizing high MW rubber similar to Hevea (1,5,6,7) and is actively being developed as a new source of natural rubber for the arid regions of the world especially in the United States.

The MW of rubber varies from 10^6 to 10^3. Rubber of MW 10^5 or less is considered unsuitable for commercial use. Unfortunately, most of the 2000 rubber synthesizing species are believed to produce rubber with a MW of ca. 5×10^4 and a unimodal MWD (6). The MWD of Hevea, however, has a bimodal distribution and shows two MW peaks. The major peak exists at a MW of ca. 7×10^5 and extends out to the 10^6 MW range. A minor peak or shoulder is also usually present which corres-ponds to a MW of ca. 5×10^4 (3,6,10,11). This bimodal MWD nearly exists for Hevea, but the amplitude of the two peaks may vary for different Hevea varieties, and is also affected by plant age and frequency of tapping (6,10). Such variation in the MWD can lead to an over-all difference in the MW average. In rubber obtained from native stands, only a high MW peak exists leading to a unimodal MWD of a high MW (1,4). Little is known about the the environmental or genetic factors influencing rubber MW in the cultivated guayule stands which would be the most likely potential source for industry. Since general husbandry and genetic variation seems to affect Hevea rubber (10), it is not unreasonable to suggest that such differences may also appear in guayule, as earlier work implied (2).

The objective of this study was to examine the MW and MWD of guayule rubber obtained from cultivated plants to see whether agronomic management can affect rubber quality. Analyses will be made on different varieties of guayule grown under different irrigation regimes and harvested at different times of the year. In addition, plants treated with bioregulators shown previously by others to increase rubber production (12) will be tested for their effects on rubber MW and MWD.

PROCEDURE:

Plant Materials. Guayule, Parthenium argentatum Gray, cultivars 593 and 11591 were planted on April 1981 in replicated plots 12.2 x 8.5 m at a planting density of 51 x 36 cm (54000 plants per ha) in Mesa, Arizona. Details on plant establishment and other related cultural practices have

been reported elsewhere (4,8). Plants from three of the six irrigation regimes were used in this study. "Wet", "medium" and "dry" moisture levels representing 12, 6 and 3 irrigations per year, respectively. Soil water contents in the profile were monitored with the neutron moisture equipment to schedule irrigation to attain the various levels of water stress in the plants. Two bioregualators, 2-(2,4-dichlorophenoxy)-triethylamine and 2-(3,4-dichlorophenoxy)-triethylamine, were applied to the plants in the field at concentration of 100 mg/L four times a year. The first application was started at the seedling stage in the greenhouse.

Another cultivar AZ-101, a cross which came available only recently, grown under a separate experiment but similar condition, was also analyzed for molecular weight.

Rubber extraction and analysis. Fresh plant samples were taken to the laboratory as soon as practicable, and the tissue fozen and then immediately ground in an electric coffee mill. A volume of packed tissue equal to ca. 2.5 ml was extracted in 10 ml of acetone for 2 h to remove the resin fraction. The actone supernatant was discarded and the pellet was dried in air for 6 to 18 h and then re-extracted with 10 ml of tetrahydrofuran (THF) for 2 h. The THF extract was filtered through a Gelman type A/E glass fiber filter. A 20 to 200 μL aliquot was injected into a gel permeation chromatograph (GPC) for molecular weight analysis. Rubber extracts were prepared from the stem, bark, xylem, leaf and flower of cultivar 593 and from the mature stem of cultivars 11593, 593, and AZ-101. Rubber analyses were made from main plant harvests in November 1983 and March 1984. Sub-samples with time were also made at other dates also. Rubber extracts from plants taken in July and August 1984 clogged the GPC column so that their data are not reported here. The GPC analyses were perfomed on a Beckman Model 330 HPLC equipped with a refractive index detector and a Nelson Analytical GPC software system. Separation of the rubber was carried out on two columns in series, one having a size exclusion of 10^7 to 10^5 (Dupont SE 4000) and the other with an exclusion limit of 10^4 to 10^3 (Waters Associate 10^4 A μ styragel). The mobile phase was THF at a flow rate of 0.6 ml per min. Standard polystyrene samples (Polymer Laboratories) were used to develop a calibration curve which was analyzed by the software.

RESULTS AND DISCUSSION:

High MW rubber was found only in the extract from the stem with none in the flower or leaf (Figure 1). This result agrees with earlier MW determinations and microscopic studies that the site of rubber accumulation is primarily in the stems (2). The rubber MW average of this particular plant (cultivar 593) harvested in March 1984 was 6.08×10^5. The MWD had a peak at about 8×10^5 with a wide tailing shoulder that extended below 10^4 MW. This shoulder has a slight flat area at ca. 10^5 which could be considered a minor peak, and suggests that a bimodal MWD exists for guayule. The peaks below 10^4 which also appear in the leaf and flower samples as well as the stem are most likely low MW non-rubber contaminants. In a plant harvested in May, the stem tissue was divided

into xylem and bark (phloem, cortex, and peridem) and other tissues were extracted and analyzed for any qualitative differences in rubber. The MWD (Figure 2) revealed no major differences, except that the MW of rubber from the bark material was slightly lower than the xylem, 4.76×10^5 versus 5.77×10^5. This was probably caused by the broader, low MW shoulder exhibited by the rubber in the bark.

There were subtle qualitative differences in cultivar 11591 rubber MWD due to irrigation regime especially for the two different early spring and mid-fall harvest dates. These materials have definite bimodal MWD (Figure 3). The MW tended to be higher in plants grown under dry conditions (March harvest) and lower in the wetter situation with increasing irrigation frequency. The drop in the MW is due to higher quantities of low MW rubber relative to the high molecular weight fraction. Similar results were observable in the November harvested plants where the MW in the dry condition was greater in the "medium" moisture level. Samples from the "wet" level, however, had slightly higher MW rubber than the "dry" one. The bimodal MW in the November samples was not as pronounced as the March harvest. Since guayule growth is much greater in March than November and growth increases rapidly with irrigation (4), the results suggest that the presence of a bimodal MWD distribution somehow reflects this growth. This is not unreasonable, since the shoulder of low MW rubber could represent the initiation of newly synthesized rubber in the process of chain elongation and polymerization, especially during spring when new shoot growth commences.

Differences in the MWD between the two varieties 593 and 11591 were subtle, but consistent, under the different irrigations treatments for plants harvested in March (Figure 4). Again, the MW dropped as irrigation was increased. The MW of cultivar 11591 was slightly higher than 593 for every irrigation level. A bimodal MWD was more evident in the medium and wet treatments for 593 and 11591, and the presence of the low MW rubber likely contributed to the lower overall MW for this variety.

Bioregulator treatments did not seem to affect the MWD of rubber as exhibited in cultivar 11591 under the "wet" condition. Since bioregulators have been reported to induce or stimulate rubber synthesis in guayule (12), one might suspect the presence of more low MW molecules; however, the data did not show this under our environmental and treatment conditions (Figure 5).

The new variety AZ-101 with rapid growth characteristics is believed to be an interspecific hybrid between the rubber producing, Parthenium argentatum and a non-rubber producing relative Parthenium tomentossum var. stramonium. This naturally produced hybrid has a morphology intermediate between the parent species, but direct evidence for such a cross to produce AZ-101 has not been established. The fast-growing and larger biomass of AZ-101 compared to existing varieties make it a desirable substitute for cultivation in rubber production. Analysis of rubber from the young plants (one year old) illustrated in Figure 6 showed that the MWD was skewed in the direction of low MW rubber compared to that of

the true guayule line such as 593. The unusual MWD of AZ-101 could mean that it contains rubber of low quality especially at this stage of development. The two varieties were harvested and analyzed in late May and both have distinct bimodal MWD. This may reflect an active stage of growth and rubber synthesis at this time of the year. Comparison of the MWD at this sampling time to that in late March (Figure 4 versus Figure 6) indicates a definite increase in the low MW rubber fraction in late May.

Lack of previous investigators (1,5,6) in describing the presence of bimodal MWD in their samples may have been due to the fact that their plant materials used were collected from wild stands growing under high water stress conditions so that relatively little low MW rubber would exist. Our results are probably the first reported GPC analysis of MWD and MW showing the presence of the bimodal type in cultivated stands. Also the results indicate that the MWD can vary considerably in rubber harvested at different times of the year and in plants of different genetic constitution. The bimodal MWD reported here appears to be related to plants in their active growth stage and may correspond to the initiation and synthesis of low molecular weight rubber which accumulates with new growth. If this is so, the results would support the hypotheis that elongation of rubber molecules follows a two step process first suggested by Hager et al.(5).

The synthesis and accumulation of high MW rubber are known in only a relatively few plants such as Hevea and guayule so that the question arises as to whether these species synthesize this high MW rubber by a two-step process, i.e., by the initiation and synthesis of a low MW rubber of ca. 5×10^4 and, a second through the elongation of these molecules by a second enzyme, which is responsible for the synthesis of the high MW rubber molecule of 10^6. In guayule, the seasonal appearance and disapperance of the bimodal MWD suggest that such a two-step process could be likely operating. One is then left with the speculation on whether the other 2000 or so rubber porducing species, which do not produce high MW rubber, may be lacking the second enzymatic step. In future work, it may be useful to study the inheritance of rubber MW and MWD in interspecific hybrids of guayule and its non-rubber producing relatives to get a better picture of the rubber synthesis process in plants.

SUMMARY AND CONCLUSIONS:

The molecular weight (MW) and the molecular weight distribution (MWD) were determined for three different guayule varieties under cultivation. The MW of guayule rubber varied between 10^6 to 10^3. Guayule showed a pronounced bimodal MWD in plants under active growth, but a unimodal distribution in quiesent or stressed plants. Irrigation frequency affected the MW and the MWD, with the MW decreasing as irrigation frequency increased, which was related to the appearance of a bimodal MWD under irrigation. The MW and MWD probably has a gentic origin, because rubber from different guayule lines grown under identical conditions show subtle differences. The recently developed interspecific hybrid

line, AZ-101, showed an unusual, bimodal MWD of predominantly low MW rubber, while the existing guayule cultivar had primarily high MW rubber. Bioregulators did not appear to change MW or MWD significantly.

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PERSONNEL: F.S. Nakayama and D.A. Bucks

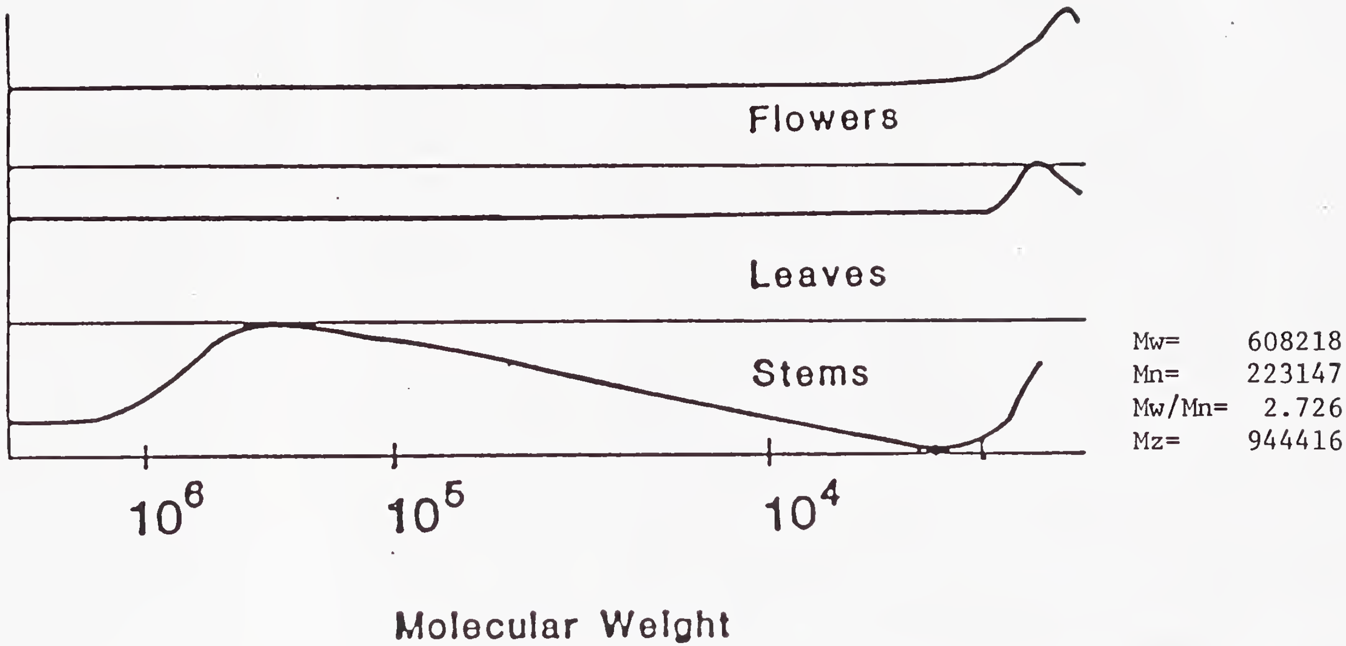


Figure 1. Molecular weight distribution of guayule rubber from the flower, leaf and stem of cultivar 593 harvested in March 1984. (Mw = molecular weight; Mn = molecular number; Mz = average molecular weight).

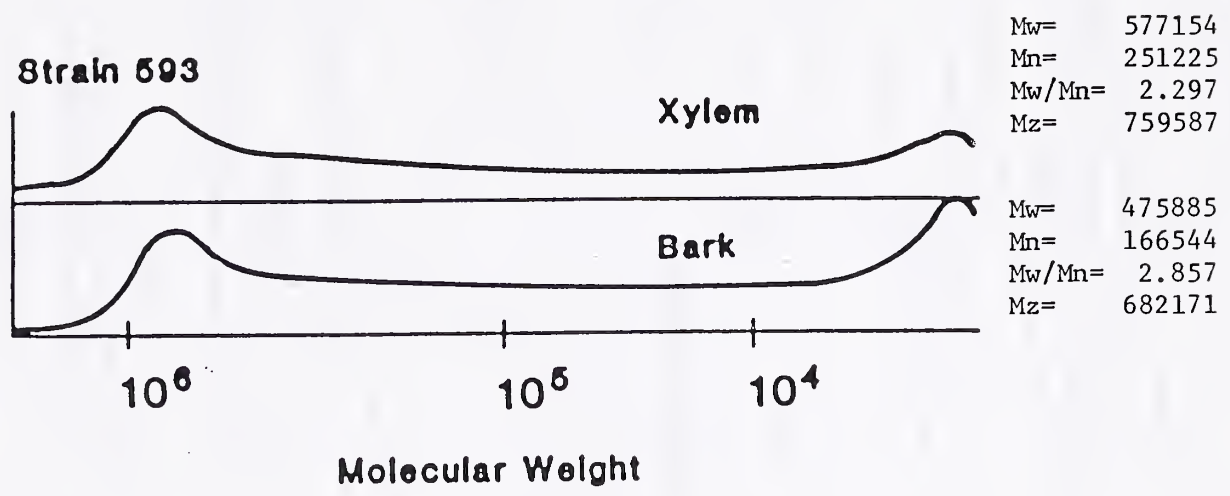
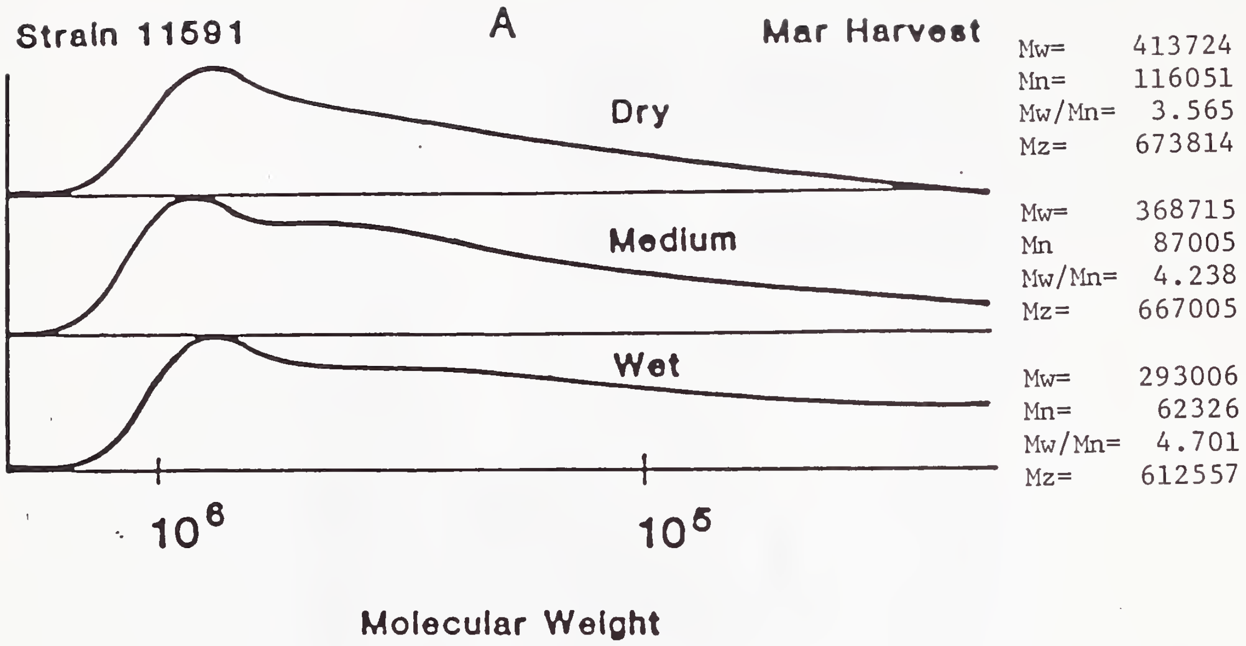


Figure 2. Molecular weight distribution of rubber extracted from the xylem and bark of cultivar 593 harvested in May 1984.



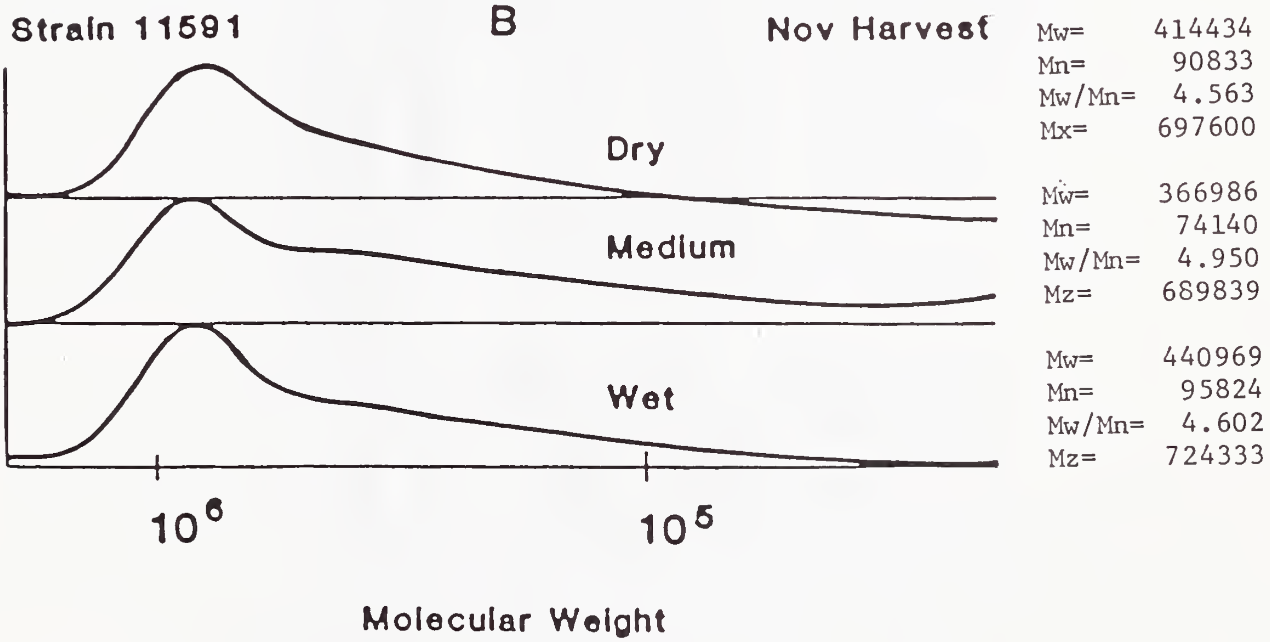


Figure 3. Molecular weight distribution of rubber for cultivars 11593 grown under three irrigation levels and harvested in November 1983 and March 1984.

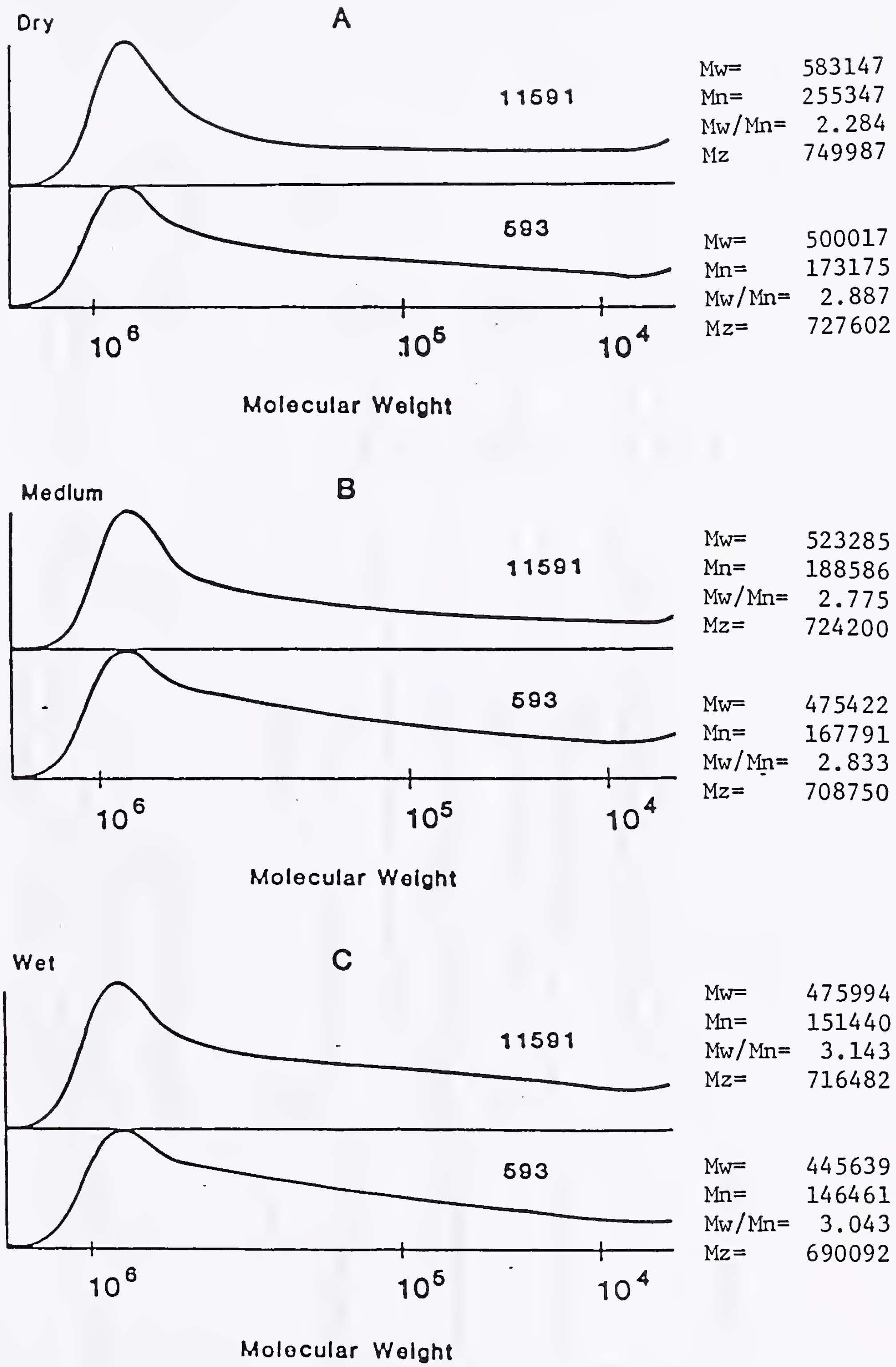


Figure 4. Comparison of molecular distribution of cultivars 593 and 11591 harvested in March 1984.

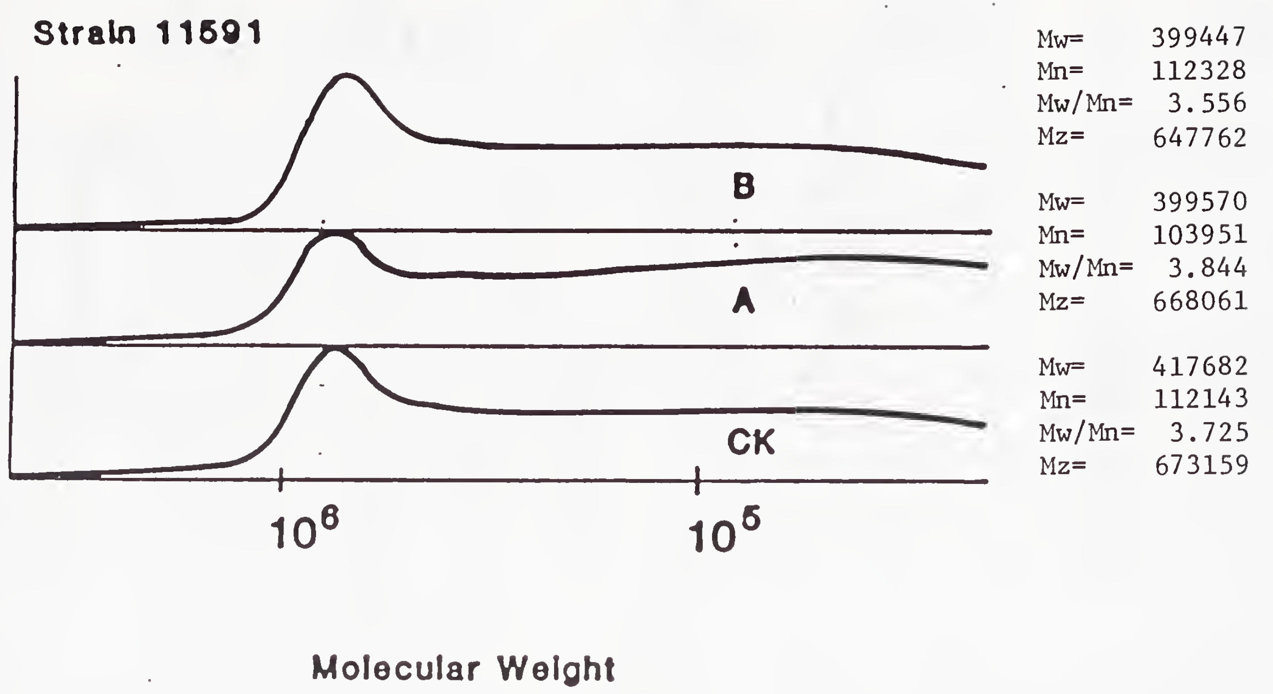


Figure 5. Molecular weight distribution of rubber from guayule plants treated with bioregulators. (A = 2-(2,4 dichlorophenoxy)-triethylamine; B = 2-(3,4 dichlorophenoxy)-triethylamine).

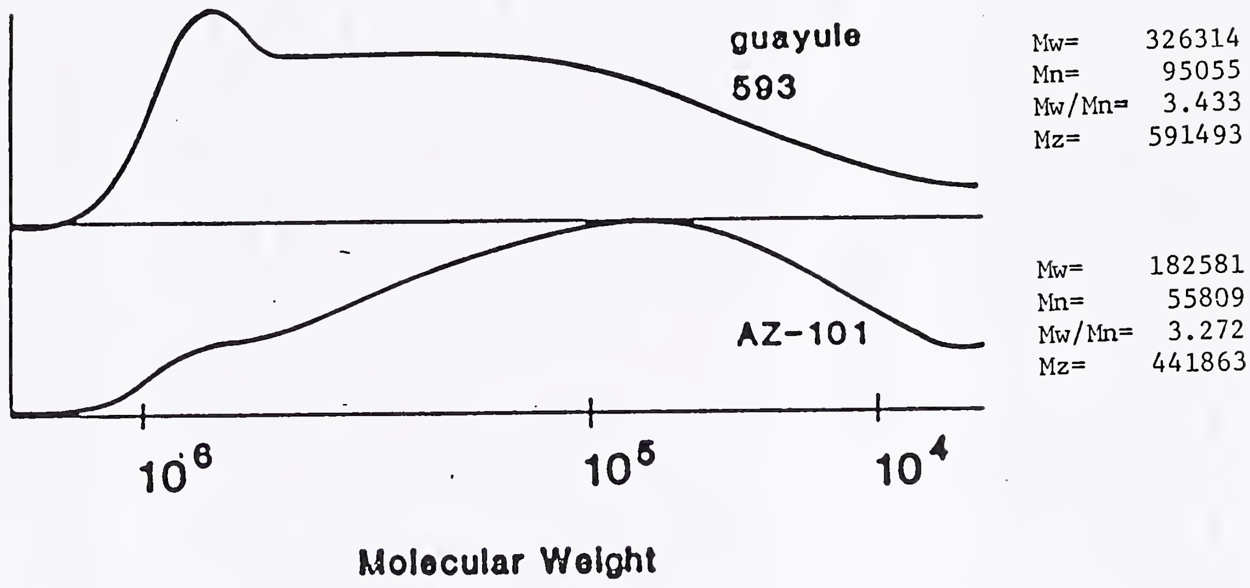


Figure 6. Molecular weight distribution of rubber from stems of cultivars 593 and AZ-101 harvested in May 1984.

TITLE: DIRECT SEEDING FOR ECONOMICAL GUAYULE RUBBER PRODUCTION UNDER DIFFERENT CLIMATIC AND SOIL CONDITIONS

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

The need to improve the economics of plant establishment of direct seeded guayule led to a series of plantings in 1982 and 1983. The specific effects of seed treatment and planting procedures, as affecting poor germination and lack of seedling vigor were investigated. Also, apparent in these two years was the pronounced effect of adverse field conditions and cultural practices. The Spring and Fall plantings of 1984 were directed towards improving germination and seedling survival rates by taking into account optimum treatments and methods of 1982 and 1983.

SPRING 1984

FIELD PROCEDURES:

Direct seeding experiments were continued in 1984 with a spring planting in Yuma, Arizona, on Superstition sandy soil (91 to 94% calcareous sand). Seed was planted in the bottom of a small corrugation 12.5-cm (5-in.) deep to accommodate the sandy soil condition and to possibly reduce damage by sandstorms. Row lengths were 152-m (500-ft) long, and irrigation water was applied by an overhead mist using an automated, lateral-move sprinkler system. Soil temperatures were taken hourly at a 1-cm and 3-cm depth and computed into a weekly average (Table 1). A new site was chosen for the 1984 plantings because of the accumulation of salts in the previously used location. Soil fumigation was not deemed necessary in the new site. Twelve rows spaced 56 cm (22 in) apart were planted on April 5, 1984, with two seeding procedures as follows: (1) pelleted conditioned seed and (2) fluid drilling of conditioned seed. Both pelleted and fluid drill were used to see if an improved pellet would perform better than previous pelleting procedures. The pelleted seeds were planted at 20 seeds/m (6 seeds/ft) intervals; whereas, the fluid drilled seeds were planted at 20 seeds/m (6 seeds/ft), 40 seeds/m (12 seeds/ft) and 80 seeds/m (24 seeds/ft). Three seed varieties or qualities (Salinas "mixed" bulk, 11591, and N56) were planted (Figure 1).

In 1984, three seeding rates, were used to cover the range from a low to moderate rate of planting. The problem with an even higher planting rate was the anticipated cost of guayule seeds. The pellets were made for the conditioned seeds using quartz sand, 2.5 percent calf gelatin, chilled at 10°C overnight and dried at 20°C for 2 days followed by planting at less than 0.2 cm (0.1 in) soil depth. The fluid drilled seeds were imbibed (partially pre-germinated before planting) for a 4-hour period in an aerated water bath, placed in Laponite 445 gel, and planted by a fluid driller on the soil surface with a light cover of

vermiculite. The rows were irrigated immediately after planting, continued daily for 8 days, and followed by watering every 3-5 days for the remainder of the trial (Table 1). No nitrogen fertilizer was applied.

In the previous two years (1982 and 1983) both conditioned (PEG + GA) and primed seed (PEG only) did equally well and improved germination rates over the untreated seeds. Because of the potential of GA for improved growth after emergence, we decided to use only the conditioned seed in 1984. All the seeds were conditioned by the U. S. Seed Research Laboratory, Beltsville, Maryland, since this seed treatment was found to be beneficial in the three previous field trials. Conditioning was performed by using a priming solution of 25 percent polyethylene glycol (PEG, MW 8000, an osmoticum to prevent water uptake injury), 0.2 percent Thiram fungicide (pH 8) with $Ca(OH)_2$, 0.5 mg/ml KNO_3 (an oxidant), and 10^{-4}M gibberellic acid (GA, a growth hormore enhancing elongation). These conditioned seeds had a laboratory germination rate of: Salinas bulk, 40 percent; 11591, 95 percent; and N565, 71 percent.

RESULTS AND DISCUSSIONS:

Seedling emergence and plant establishment was uniform for the 1984 spring planting. In comparison with earlier experiments where plant survival declined after germination before becoming consistent, the plant counts were almost constant after emergence on all treatments. Both the pelleted and fluid drilled seeds began to emerge about 6 to 7 days after planting. A total of 362 mm (14 in) of irrigation water was applied during the 3-month establishment period (Table 1). Field germination rates based on the total number of seeds planted averaged 9, 36, and 30 percent, respectively, for the bulk, 11591, and N565 seed varieties at the end of establishment period as shown in Table 2. The germination rates were nearly twice as much for the fluid drilled over the pelleted seeding methods. Plant survival rates (field germination divided by maximum expected laboratory germination) were about 40 percent for the good-quality, 11591 and N565 seeds but less than 21 percent for the lower-quality, bulk seeds (Figure 2). Based on these plant survival rates, planting rates between 20 and 40 seeds/m (6 and 12 seeds/ft) would be recommended for guayule seeds having a laboratory germination rate of better than 70 percent, whereas a planting rate of more than 40 seeds/m (24 seeds/ft) would be required for lower-quality seeds. Some of the possible reasons for less than maximum germination or survival rate in the field are problems associated with seedling vigor, salt tolerance, seedling diseases, weed control, and other environmental conditions (wind, soil and air temperature, rainfall, etc.).

For the 1984 fall planting, seedling emergence was very poor because direct seeding was made too soon after the pre-plant, contact herbicide was applied for weed control. Since temperatures were cool, the herbicide persisted in the sandy soil for at least 3 to 4 weeks. Several greenhouse investigations and laboratory analyses were conducted to verify that seedling germination was limited by the herbicide; and a second, smaller direct seeding experiment was conducted on November 15 to demonstrate that the guayule seeds would germinate properly in the sandy soil.

SUMMARY AND CONCLUSIONS:

Direct seeding of guayule in the field has shown considerable promise where the seeds are conditioned with polyethylene glycol and gibberellic acid, planted using pelleting or fluid drilling techniques, and precisely irrigated being careful not to under or over irrigate. Planting rates between 20 and 40 seeds/m (6 and 12 seeds/ft) were adequate to obtain moderate plant populations when the guayule seeds have an initial germination rate of more than 70 percent. Although satisfactory stands were achieved with the conditioned seeds, guayule seedling vigor and salt tolerance are possibly the two main problems that need to be solved before direct seeding can be recommended for the establishment of this crop under semiarid conditions. Direct seeding studies on guayule will continue with two planting dates in April and May, 1985 on the sandy soil. Three seed varieties and planting rates will again be used, but the planting of pelleted seed will be replaced by planting raw conditioned seeds with a new precision planter in addition to fluid drilling. Five irrigation treatments will be included if a uniform stand is attached, and weed control procedures will be improved.

PERSONNEL: D. A. Bucks and O. F. French (U. S. Water Conservation Laboratory); G. R. Chandra (U. S. Seed Research Laboratory); and R. L. Roth and D. E. Powers (University of Arizona)

Table 1. Weekly water application, nitrogen application, precipitation, class A pan evaporation, average maximum and minimum air temperatures, and average maximum and minimum soil temperatures at 1- and 3-cm soil depths, at Yuma, Arizona, Spring 1983.

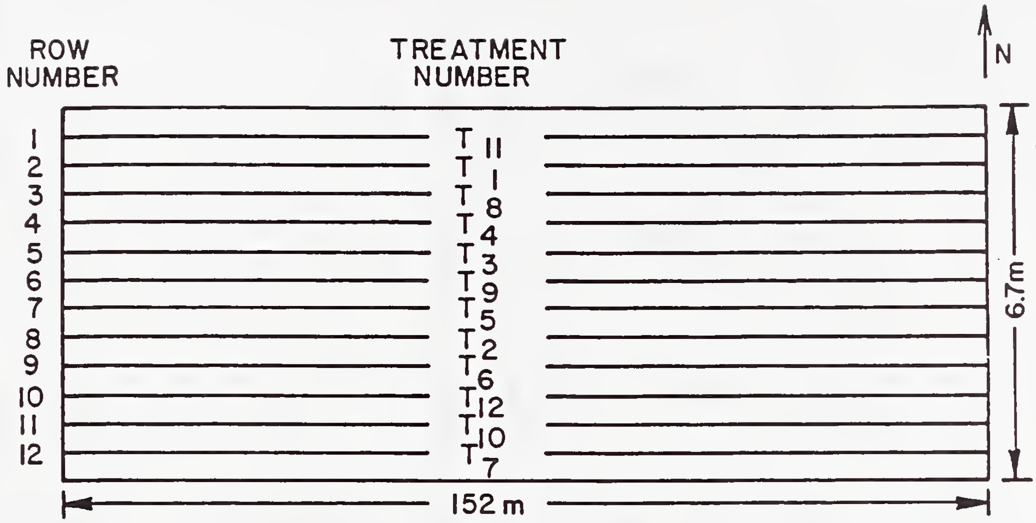
Dates	Water Applied (mm)	Nitrogen Applied (kg/ha)	Precipitation (mm)	Class A Pan Evaporation (mm)	Average Air Temp °C Max	Average Air Temp °C Min	Average Soil Temperature, °C 1-cm Max	1-cm Min	3-cm Max	3-cm Min
5-13 Apr	66.5	0	9.9	64.8	28	11	30.4	12.5	27.7	12.4
14-20 Apr	29.0	0	0	61.5	34	13	36.4	15.1	31.5	15.5
21-27 Apr	9.9	0	0	65.6	29	9	34.3	13.4	30.7	13.3
28 Apr-4 May	9.4	0	1.0	50.4	28	10	35.5	14.4	32.2	14.1
5-11 May	11.2	0	0	75.7	36	16	41.2	19.4	37.8	19.3
12-18 May	27.4	0	0	14.9	37	17	40.3	20.0	38.1	19.7
19-25 May	23.9	0	0	83.0	39	18	42.9	19.1	41.2	20.5
26 May-1 Jun	14.5	0	0	86.5	43	21	43.0	22.8	42.9	23.1
2-8 Jun	43.4	0	0	73.5	35	19	34.9	21.9	35.8	21.0
9-15 Jun	27.9	0	0	76.3	36	18	35.5	24.1	37.3	22.0
16-22 Jun	29.5	0	0	78.6	39	17	37.2	24.2	38.8	22.1
23-29 Jun	27.2	0	0	70.0	40	25	--	--	--	--
30 Jun-6 Jul	28.7	0	0	78.7	42	23	--	--	--	--
7-13 Jul	13.5	0	0	80.3	41	27	--	--	--	--
Total or Average	362.0 (14.3 in)	0 (0)	10.9 (.40 in)	1019.8 (40.1 in)	32.6 (98°F)	17.4 (63.4°F)	37.4 (99.3°F)	18.8 (65.8°F)	35.8 (96.4°F)	18.5 (653°F)

Table 2. Field germination rates after 3 months based on the total number of seeds planted on April 5, 1984.

Planting Methods	Seeding Rate	Seed Variety 1/ bulk	11591	N565	Average
	(seeds/m)	(percent germination)2/			
pelleted seeding	20	7	27	14	16
fluid drilled	20	12	39	38	30
seeding	40	8	42	34	28
	80	8	37	33	26
average (percent germination)		9	36	30	

1/ Laboratory germination: bulk = 40 percent, 11591 = 95 percent, and N565 = 71 percent

2/ Average of 3 replicates



	SEED TREATMENT	PLANTING METHOD	SEED CULTIVAR	SEEDING RATE
T_1	CONDITIONED, WITH GA	PELLET	N565	20 seeds/m
T_2	CONDITIONED, WITH GA	PELLET	11591	20 seeds/m
T_3	CONDITIONED, WITH GA	PELLET	MIXED BULK	20 seeds/m
T_4	CONDITIONED, WITH GA	FLUID DRILL	N565	20 seeds/m
T_5	CONDITIONED, WITH GA	FLUID DRILL	N565	40 seeds/m
T_6	CONDITIONED, WITH GA	FLUID DRILL	N565	80 seeds/m
T_7	CONDITIONED, WITH GA	FLUID DRILL	11591	20 seeds/m
T_8	CONDITIONED, WITH GA	FLUID DRILL	11591	40 seeds/m
T_9	CONDITIONED, WITH GA	FLUID DRILL	11591	80 seeds/m
T_{10}	CONDITIONED, WITH GA	FLUID DRILL	MIXED BULK	20 seeds/m
T_{11}	CONDITIONED, WITH GA	FLUID DRILL	MIXED BULK	40 seeds/m
T_{12}	CONDITIONED, WITH GA	FLUID DRILL	MIXED BULK	80 seeds/m

Figure 1. Field diagram for direct seeding experiment of guayule seeds in the spring 1984 at Yuma, AZ.

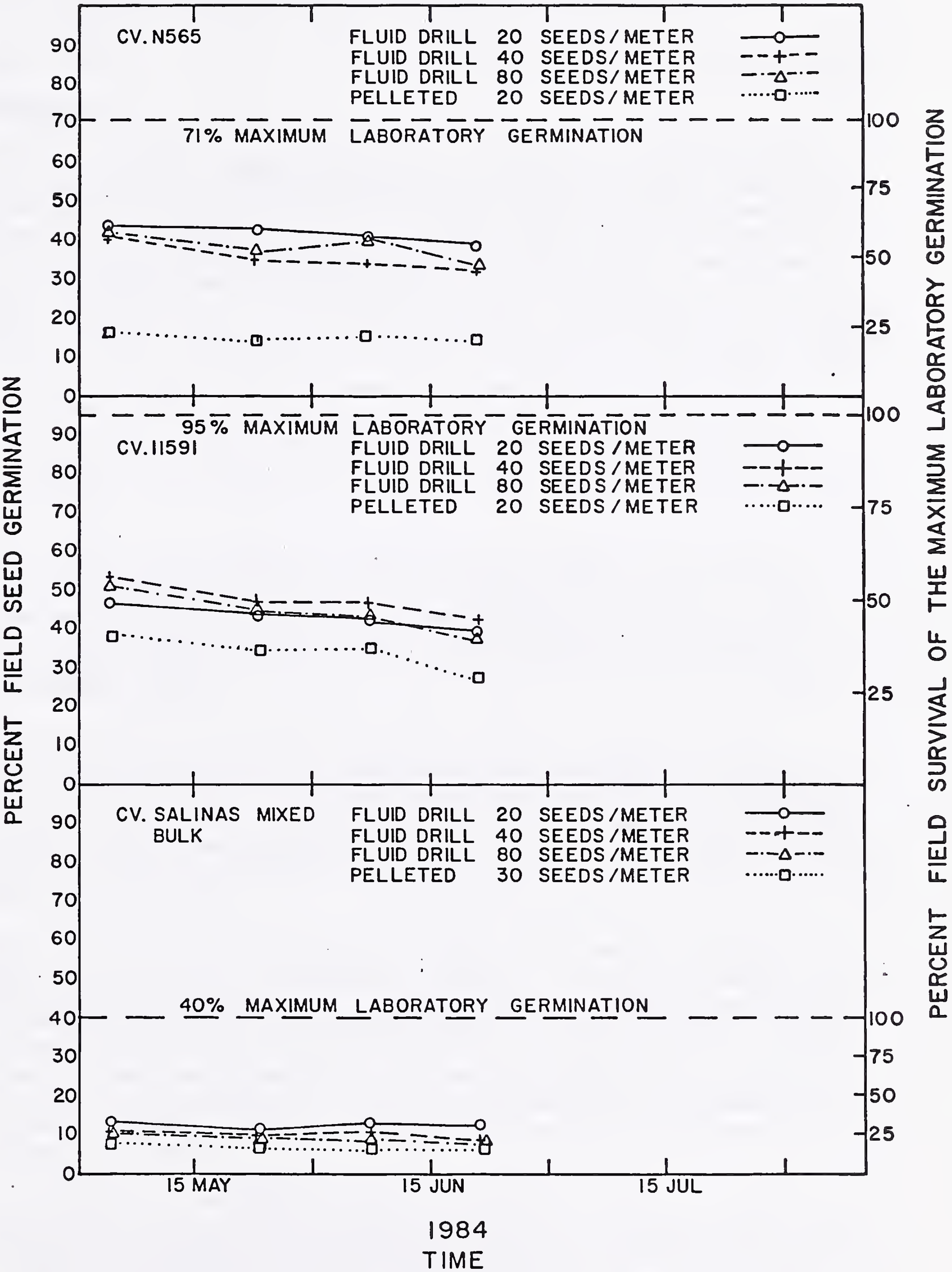


Figure 2. Percent seed germination and field seedling survival by seed cultivar, planting method, and planting rate in the Spring 1984 at Yuma, Arizona.

TITLE: THE EFFECTS OF PLANT BIOREGULATORS ON GUAYULE RUBBER AND RESIN PRODUCTION AND SELECTED PHYSIOLOGICAL CHARACTERISTICS

NRP: 20740 CRIS WORK UNIT: 5510-20740-012

INTRODUCTION:

Guayule (Parthenium argentatum Gray), a xerophytic rubber producing shrub indigenous to the Chihuahuan Desert of north-central Mexico and the adjacent Big Bend area of southwestern Texas, has the potential to become a domestic source of natural rubber with quality comparable to the tropically-adapted Hevea brasiliensis (Ray, 1983). Guayule is a highly-branched, symmetrically-shaped perennial shrub of the Compositae Family (Lloyd, 1911). In its native habitat, guayule grows to a maximum height of about 1 m at elevations between 610 and 1830 m on well-drained calcareous soils receiving 25 to 30 cm of rainfall annually (Ray, 1983). In addition to high quality rubber, the guayule plant also produces resins with potential commercial applications as coatings for water resistance and as peptizers (prooxidants) used in rubber processing (Belmares, et al., 1980). The bagasse may be used as pulp for paper, as a feedstock, and as a fuel to power the rubber processing plants (Ray, 1983).

At the present time, however, guayule rubber yields are too low to attract commercial production. It is estimated that guayule rubber yields must double to make the crop economically feasible at current rubber prices (Wright et al., 1984). This situation may change, however, with changes in the price and availability of sources of Hevea and synthetic rubber.

Guayule breeding efforts are currently underway to increase rubber yields, but it may be five or more years before significant progress is realized (Rubis, 1984). The anticipated progress through breeding may be delayed even further by the complex genetic and reproductive system which guayule has been shown to possess. Guayule plants have been found with several ploidy levels and may produce seed either by amphimixis or apomixis (Ray, 1983).

Another means of increasing guayule rubber yields may be through the application of plant bioregulating substances. Studies by Hayman et al., (1974), Hayman and Yokoyama (1976) and Hsu et al., (1974) demonstrated the chemical bioinduction of tetraterpenoids in carotenogenic tissue. Yokoyama et al., (1977) concluded that these bioregulators result in increased synthesis of enzymes in the tetra-terpenoid pathway through a process of gene derepression. These studies led to the hypothesis that application of plant bioregulators may increase cis-polyisoprenoid synthesis in guayule.

The compound 2-(3,4-dichlorophenoxy)triethylamine (DCPTA), in particular, has shown promise as a bioregulator for increasing polyisoprenoid rubber production of guayule. The initial studies by Yokoyama et al. (1977) resulted in 2.7- to 4.3-fold increases in percent rubber

content of four-month-old greenhouse-grown and eight-month-old field-grown guayule, respectively. The plants in these studies were treated with 5000 ppm DCPTA and sampled three weeks after treatment. While the percentage increase in rubber due to DCPTA treatment appeared to be substantial, the average rubber content of the plants increased from only 1.25 to 3.47 % in the greenhouse and from .91 to 3.03 % in the field. Rubber percentages of mature guayule plants may be as high as 20 % or more (Hammond and Polhamus, 1965).

Benedict et al., (1983) reported a two-fold increase in percent rubber of DCPTA-treated greenhouse-grown guayule. Ten-week-old plants were treated with 5000 ppm of DCPTA at a rate of 5 ml per plant. DCPTA treatment also resulted in a 1.5 to 3.0 fold increase in the activity of the enzymes mevalonic acid kinase, isopentenyl pyrophosphate isomerase, and rubber transferase, all of which are involved in the synthesis of cis-polyisoprene. DCPTA had no effect on plant dry weight.

Further research by Hayman et al., (1983) demonstrated that lower concentrations of DCPTA (125 and 500 ppm) applied at higher rates (100 ml per plant) resulted in higher rubber yields. A 91% increase in rubber yield per plant was reported. There was no significant increase in percent rubber of the samples, however. The higher rubber yields were, therefore, due to a DCPTA-induced increase in plant biomass, not percent rubber. It should be noted that with the 100 ml per plant application rate used in this study it would be necessary to apply a volume of 2875 l ha^{-1} for a planting density of 28,750 plants ha^{-1}, a volume which is impractically large for commercial production. It may be more practical to increase the DCPTA concentration of the solution and apply smaller volumes per plant.

More recent studies by Bucks et al., (1984) showed no significant effects of DCPTA applied to field-grown guayule. Plants in Yuma, Arizona, were treated with 100 ppm DCPTA at a rate of 100 ml per plant four times during 1982 and 350 ml per plant applied four times during 1983. The low concentrations of DCPTA, even at high application rates, were unsuccessful in promoting rubber yields, either by way of increasing percent rubber or plant biomass.

These reports on the effects of DCPTA on guayule rubber yield appear to be contradictory, but a lack of consistent and repeatable results from bioregulator studies are not unusual. Bhalla (1981) has outlined the "consistently inconsistent" results obtained through experimentation with the plant growth regulator triacontanol. The growth regulator mepiquat chloride has also produced inconsistent results when applied to cotton (Briggs, 1981), and the effects have been highly sensitive to environmental conditions.

Guayule leaves are covered with a very hard, high molecular weight wax (C 48 to C 54) (Palu and Garrot, 1983 and Ray, 1983). The thickness of the leaf wax is influenced by environmental conditions and plant age, with older plants and plants subjected to drought having the thicker layer of wax on their leaves (Lloyd, 1911). Differences in environmental

conditions and subsequent differences in cuticle thickness preceding application of bioregulators may restrict the entry of the bioregulators into the leaves, and may account for the differences reported for DCPTA effects.

The results of DCPTA applications to guayule, while inconsistent, indicate a potential for its use in improving guayule rubber yield. No studies have yet been reported, however, which address the questions of application rates, application timing, or number of applications for optimum rubber yields. Nor has the chemical nature of DCPTA been investigated with respect to solubility, leaf penetration, or mobility within the plant. The objective of this study is to investigate the preceding questions as well as study the effects of DCPTA on photosynthesis, plant water balance, and other selected physiological processes.

PROCEDURES:

Three separate studies were initiated to investigate the effects of DCPTA on rubber and resin production and selected physiological characteristics of guayule. All guayule material used in these studies was cv. N 565 II. The DCPTA used in these studies was synthesized and provided by Dr. Henry Yokoyama, U.S. Fruit and Vegetable Chemistry Laboratory, USDA-ARS, Pasadena, CA 91106.

Maricopa AZ, Field Studies:

A total of 960 guayule seedlings (cv. N 565 II) were transplanted from the greenhouse into the field at the University of Arizona Maricopa Agricultural Center on November 15, 1984. The soil type is Casa Grande sandy clay loam. The 10 to 15 cm tall seedlings were transplanted using a single row mechanical transplanter into beds spaced 100 cm apart. Plant spacing within rows was 45 cm. An experimental unit consisted of four rows with 10 plants per row for a total of 40 plants per plot. Treatment of the plots with DCPTA will begin in March of 1985 and continue through December 1986. The treatment descriptions are outlined in Table 1. The DCPTA applications are designed to investigate the effects of time of application (spring, summer, fall, or winter) and the total number of applications (two, four, or eight) over a two year period. All DCPTA solutions will be at 5000 ppm concentration and include a commercially available surfactant at the recommended concentration.

Plants will be sprayed with a volume that thoroughly wets the adaxial side of all leaves. This volume will necessarily increase with each subsequent application date as the plants mature. Samples will be harvested twice for analysis of rubber and resin content; once in February 1986 and again in February 1987. Harvested plants will be allowed to dry at air temperature for approximately two weeks before being processed for rubber and resin analysis. Three subsamples, each consisting of two plants, will be harvested from each plot on both harvest dates. Rubber and resin content will be determined by a double-extraction

gravimetric procedure (Black et al., 1983). Rubber and resin content data will be analyzed with an ANOVA for a randomized complete block design with subsampling (Steel and Torrie, 1980).

Leaf transpiration, diffusive resistance, and temperature differential will be measured on cloudless days twice weekly from April through October with a Licor 1600 steady state porometer. Two fully expanded leaves near the top of two plants will be sampled in each plot. Each trait will be subjected to a repeated measures ANOVA and a regression analysis as described by Finlay and Wilkinson (1963).

One plant will be harvested from each plot monthly between February 1985 and February 1987 for fresh weight, dry weight, and leaf area measurements. Plant heights of four plants in each plot will be measured weekly between January 1985 and February 1987.

Volumetric soil water content will be measured weekly begining in March 1985 with a Campbell Pacific Nuclear model 503 neutron moisture meter. Access tubes are located in the middle of one of the inner two beds in each plot in blocks I and II to a depth of approximately 260 cm. Measurements will be taken between 20 and 220 cm at 20 cm intervals. Soil water content data will be used to determine if the DCPTA-treated guayule exhibit different water extraction patterns and to study soil moisture by DCPTA treatment interactions with transpiration, diffusive resistance, and temperature differential.

USWCL, Field Study:

A total of 720 two-month-old guayule seedling (cv N 565 II) were transplanted from the greenhouse into field plots at the U.S. Water Conservation Laboratory. One half of the plots in each of two blocks were planted on October 12, 1984 and the rest of the plots were planted on March 7, 1985. The plots were rotatilled to 15 cm and fertilized with 50 lb per acre N as ammonium phosphate on October 11, 1984. The soil type is an Avondale clay loam.

An experimental unit consists of 3 rows of 12 plants, with 30 cm row spacing and 15 cm between plants within a row. The treatments will consist of four concentrations of DCPTA (750, 1500, 3000, and 6000 ppm), with each treatment solution containing a commercial wetting agent at the recommended rate. The four DCPTA treatments and a control will be completely randomized in each of four blocks. Application of treatments will take place during April 1985.

Each block contains one centrally located 260 cm deep access tube for measurements of volumetric soil water content with the neutron moisture probe. Soil moisture content will be measured weekly throughout the experiment as an aid in scheduling irrigation. Water will be delivered to the plots through a surface drip irrigation system.

Plants will be harvested twice for analysis of rubber and resin content; at 90 and 180 days after treatment. Three subsamples, each consisting

of two plants, will be harvested from each plot on each harvest date. The rubber and resin determinations will be conducted as described earlier.

Apparent photosynthesis (AP) will be measured on two consecutive days each week beginning the first week after treatment with a Licor 6000 portable photosynthesis measurement system. The same plant in each plot will be used for AP measurements for a given week. After the second measurement the plant will be harvested and the leaf area measured to allow for calculation of AP on a leaf area basis. Fresh weight and dry weight of these plants will also be measured. Plant height of four plants in each plot will be measured each week. The data will be analyzed using an ANOVA regression analysis.

USWCL, Greenhouse Study:

Several hundred guayule seedlings (cv N 565 II) were started in medium-grained vermiculite in the greenhouse between 7 and 15 January 1985. After one month, 240 seedlings of uniform size were transplanted into 6.6 l pots containing a peat-vermiculite mix (3:1 v:v). The plants were fertilized with full strength Hoagland's solution (Hoagland and Arnon, 1950) three times each week. At 2 months of age the plants were treated with DCPTA solutions of 375, 750, 1500, 3000, and 6000 ppm in combination with and without 1 % dimethylsulfoxide (DMSO) and a commercial surfactant. A complete list of treatment combinations is listed in Table 1. DMSO is being investigated because of its solvent properties which may enhance penetration of DCPTA through the thick waxy layer of the guayule leaves (Jacob et al., 1964).

Three greenhouse benches will delineate each of three blocks. Each treatment will be applied to five individual plants (five subsamples) within each block. Treatments and subsamples within each block will be completely randomized. Plant height of each plant will be measured each week for two months following treatment application. Plants will be harvested two months after treatment. Material from each plant will be separated into leaf, stem, and root and crown tissue for fresh and dry weight measurement prior to rubber and resin analysis as previously described.

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<u>PERSONNEL</u>: S. G. Allen, F. S. Nakayama, and D. A. Bucks

Table 1. Bioregulator treatments applied to guayule at the Maricopa Agricultural Center during 1985 and 1986.

Treatment #	Time of Application	Number of Applications
1	control	0
2	Spring 1985, 1986	2
3	Summer 1985, 1986	2
4	Fall 1985, 1986	2
5	Winter 1985, 1986	2
6	Spring, Summer, Fall, Winter 1985	4
7	Spring, Summer, Fall, Winter 1986	4
8	Spring, Summer, Fall, Winter 1985, 1986	8

Table 2. Treatment combinations applied to greenhouse-grown guayule during March 1985.*

Treatment Number	DCPTA (ppm)	DMSO (%)	Surfactant
1	0	0	no
2	0	0	yes
3	0	0	yes
4	375	0	yes
5	750	0	yes
6	1500	0	yes
7	3000	0	yes
8	6000	0	yes
9	375	1	yes
10	750	1	yes
11	1500	1	yes
12	3000	1	yes
13	6000	1	yes
14	3000	1**	yes

* In 250 ml volume.

** DMSO applied 24 hours prior to DCPTA application for treatment number 14.

TITLE: SOIL-PLANT-ATMOSPHERE INTERACTIONS AS RELATED TO WATER CONSERVATION AND CROP PRODUCTION

NRP: 20760 CRIS WORK UNIT: 5422-20760-003

INTRODUCTION

Another banner year for our research group. In order to comply with the Paperwork Reduction Act, only our most significant publications will be presented in this report. We had 60 papers published, 41 are in press and 3 are in the journal review process. Many papers were of the book review type. There are numerous manuscripts in various stages of completion, which you will read about next year.

Two papers describe the use of remotely sensed parameters to evaluate components of the surface energy balance. One discusses the use of reflected and emitted radiation as inputs to calculate net radiation, and the other incorporates surface temperature to evaluate actual evapotranspiration. The potential use of remote sensing in farm management decision making is the subject of three papers. The first deals with the relationships between spectral data and crop and soil properties. Irrigation scheduling using crop temperature is detailed in the other two papers. Using spectral reflectance to describe crop and soil conditions is the subject of 6 papers. One paper describes how information from a multiband sensor can be used to calculate total reflected solar radiation. A second paper evaluates the temperature stability of such a radiometer. Discriminating soil and vegetation under partial canopy conditions is the subject of two papers, and one paper describes how various vegetation indices are correlated with various plant parameters for winter wheat. Another paper addresses the combined effect of sun angle and canopy architecture on the reflectance of wheat cultivars.

Three papers deal with the use of canopy temperature to describe plant behavior. The first discusses the stability of non-water-stressed baselines for two types of plants, wheat and water hyacinths. A second hyacinth study examined the stomatal conductance and net photosynthesis responses to a suddenly-induced stress. Canopy temperature of sunflower was simulated from weather station data from which root-zone soil water potential was inferred.

The effect of CO_2 on plants and climate is examined in four papers. One deals with how water hyacinth responds to increased atmospheric CO_2, and the other three address the issue of how world climate many respond to CO_2 increases, and what the potential effect on streamflow will be. A single paper reports the findings of how aquatic vegetation influences evaporative losses from ponds and reservoirs. Four reports are included in this year's annual publication. The first describes work in progress on the effects of CO_2 enrichment of agave, fresh-water algae and water hyacinths. A study was initiated and completed to evaluate the stability of the calibration coefficients of net radiometers over vegetated

and bare soil surfaces. A brief description of a recently acquired remote image processing system is also included in this report. And, finally, we describe the most recent experiment in our backyard where we use remote sensing techniques to characterize the growth and behavior of alfalfa.

ENERGY BALANCE

Reginato, R. J., Jackson, R. D., and Pinter, P. J., Jr. Evapotranspiration calculated from remote multispectral and ground station meteorological data. Remote Sensing of Environment. (In press)

Evapotranspiration was evaluated by combining remotely sensed reflected solar radiation and surface temperatures with ground station meteorological data (incoming solar radiation, air temperature, wind speed, and vapor pressure) to calculate net radiation and sensible heat flux. Soil heat flux was estimated as a fraction of the net radiation. Instantaneous values of ET were calculated for 18 wheat plots for 44 cloudless days over a growing season. Three of the 18 plots contained lysimeters which provided data to compare against the instantaneous values. For the remaining plots, daily ET was estimated from the instantaneous data and compared with values calculated from soil water contents measured with a neutron moisture meter. For generally clear sky conditions, the comparisons indicated that ET could be adequately evaluated using a combination of remotely sensed and ground-based meteorological data. The results suggest that ET maps of relatively large areas could be made using this method with data from airborne sensors. The extent of the area covered appears to be limited by the distance that air temperature and windspeed data can be extrapolated.

Jackson, R. D., Pinter, P. J., Jr., and Reginato, R. J. Net radiation calculated from remote multispectral and ground station meteorological data. Agricultural and Forest Meteorology. (In press).

Of the four terms that comprise net radiation, the incoming solar and the longwave radiation from the atmosphere are essentially independent of surface conditions (e.g., bare soil, vegetation). These terms can be measured at a single location using ground-based instruments and extrapolated over relatively large areas. The reflected solar and the emitted longwave terms are surface dependent, but are amenable to measurement by remote means. A method is described whereby net radiation is evaluated by combining ground-based meteorological and remote multispectral measurements. Net radiation values obtained using the remote method were compared to values obtained using miniature net radiometers. The net radiometers were positioned near the center of 18 wheat plots and the multispectral measurements were made over a 6 m transect on each plot. Although the two methods used instruments having different fields-of-view, good agreement was obtained. The results imply that, by combining ground-based and remote measurements, net radiation maps of relatively large areas can be constructed at the level of detail determined by the resolution element of the multispectral radiometer.

FARM MANAGEMENT

Jackson, R. D. Remote Sensing of Vegetation Characteristics for Farm Management. SPIE Vol. 475, Remote Sensing. pp. 81-96.

The potential for remotely sensed data being used by farmers in making day-to-day management decisions has not been fully realized because the data have generally not been available in real-time. Furthermore, the relationships between spectral data and crop and soil properties have yet to be incorporated into the expert systems necessary for rapid data analysis and interpretation. This review details some major requirements for a farm oriented remote sensing system, and evaluates the state-of-the-art concerning relationships between spectral data and crop and soil properties. Current and proposed remote sensing systems geared toward farm management are discussed.

Reginato, R. J., and Howe, J. Irrigation scheduling using crop indicators. J. Irrig. and Drainage Engin. (In press).

Petiole water content and canopy temperature of cotton were used as indicators of stress in cotton. A crop water stress index (CWSI) using remotely sensed canopy temperature was a better indicator of plant stress then was petiole water content. This point was most evident when using these parameters as a potential tool for scheduling irrigations and for estimating lint cotton yield. From these results we conclude that a CWSI, using canopy temperature, is a sensitive indicator of crop stress. Both CWSI indices evaluated, give similar results, and a user should choose the one which suits his conditions best. The CWSI may be used for scheduling irrigations and for estimating lint cotton yield prior to harvest. Petiole water content, on the other hand, does not appear to possess the sensitivity of a CWSI for assessing crop stress. Additionally, PWC involves a labor intensive destructive plant sampling procedure which yields data for a single plant part, whereas a CWSI is derived from a measurement that surveys many plants. For a rapid assessment of crop stress to schedule irrigations and to estimate yield, it seems appropriate to use the CWSI.

Reginato, R. J. Plant stress and irrigation scheduling. Proc. Conf. on the Application of Remote Sensing to Agriculture. Univ. of Arizona, College of Agriculture, Casa Grande, AZ. pp. 37-44.

Scheduling irrigations using traditional soil and atmospheric techniques is contrasted with a relatively new method using remotely sensed crop temperature. A hand-held infrared thermometer was used to assess plant stress for both wheat and cotton in two field experiments. It was shown that plant stress decreased to a minimum value about 3 to 5 days following an irrigation and then increased until the next irrigation. The applicability of the remote sensing technique to schedule irrigations was demonstrated.

SPECTRAL REFLECTANCE

Jackson, R. D. Total reflected solar radiation calculated from multiband sensor data. Agric & Forest Meteorol., 33:163-174.

Reflected solar radiation is a significant term in the net radiation equation and is the one most strongly affected by surface conditions. The evaluation of net radiation over a heterogeneous area requires a detailed knowledge of the areal distribution of the reflected solar radiation. Remote sensing offers a means to obtain this areal distribution, provided that the total reflected solar spectrum can be estimated from discrete band multispectral radiometric data. A radiative transfer model was used to calculate the irradiance at the earth's surface for a number of atmospheric scattering and absorption conditions. Response functions of two multiband radiometers were used to obtain the partial spectrum/spectrum (P/T) ratio for each radiometer at each atmospheric condition. It was found that the P/T ratio was essentially independent of atmospheric scattering and only mildly dependent on water vapor absorption. Reflectance spectral distributions for 14 different surface conditions (bare soil to full green canopy) were used along with the irradiance data to determine the P/T ratio for reflected solar radiation. Multispectral data, with the appropriate P/T ratio, were used to calculate the total incoming radiation and the total reflected radiation from a wheat canopy. The calculated data differed from wide band pyranometer data by about 5%. It was concluded that both total incoming and reflected solar radiation can be evaluated from multispectral radiometric data. This development is a step towards regional net radiation maps, and possibly regional evapotranspiration maps.

Jackson, R. D., and Robinson, B. F. Field evaluation of the temperature stability of a multispectral radiometer. Remote Sensing of Environ., 17:103-108.

Measurements of radiance from a calibrated barium sulfate painted reflectance panel, made during the course of routine field experiments, were used to evaluate the effect of detector temperature on the voltage output from silicon (Si) and lead sulfide (PbS) detectors of a multiband spectral radiometer. The four Si detectors were found to be nearly independent of temperature changes. However, the voltage output from the three PbS detectors decreased linearly with increasing detector temperature at a rate of 4 to 5%°C^{-1}, which is considerably more than expected from manufacturer's specifications for the instrument. The error in reflectance values caused by a detector temperature change of 1°C was less than 0.25% of value for the Si detectors, but was about 2.5% of value for the PbS detectors. A correction factor was derived to adjust measured voltages to a reference temperature and to compute corrected reflectances. The correction factor can be derived from analysis of field instruments of radiance from a calibrated reflectance panel, if the detector temperature is known at the time of measurement.

Pinter, P. J., Jr., Jackson, R. D., Ezra, C. E., and Gausman, H. Sun angle and canopy architecture effects on the spectral reflectance of six wheat cultivars. International Journal of Remote Sensing. (In press).

Canopy spectral reflectances were measured over six cultivars of spring wheat (Triticum aestivum L.) grown at Phoenix, AZ. Data were collected at 30 to 45 minute intervals on 9 March 83 using two ground-based radiometers with bandpass characteristics similar to those of the multispectral scanner and thematic mapper on Landsat 4 and 5. Major differences in reflectance were observed among cultivars at every time period despite their apparent similarities in green leaf area and green biomass. Single-leaf spectra measured in the laboratory with a spectrophotometer revealed no cultivar-related differences and supported the contention that the reflectances were strongly influenced by canopy architectural features. The diurnal patterns of reflectance reinforced this conclusion with planophile canopies exhibiting the least amount of variability due to changes in sun angle and erectophile canopies showing the most. These data underscore the complexities of interpreting remotely sensed multispectral data and suggest that multiple sun angle data acquisitions may be required to extract desired information.

Huete, A. R., Jackson, R. D., and Post, D. F. Spectral response of a plant canopy with different soil backgrounds. Remote Sensing of Environ., 17:37-53.

The spectral behavior of a cotton canopy with four soil types alternately inserted underneath was examined at various levels of vegetation density. Measured composite spectra, representing various mixtures of vegetation with different soil backgrounds were compared with existing measures of greenness, including the NIR-Red band ratios, the perpendicular vegetation index (PVI) and the greenness vegetation index (GVI). Observed spectral patterns involving constant vegetation amounts with different soil backgrounds could not be explained nor predicted by either the ratio or the orthogonal greenness measures. All greenness measures were found to be strongly dependent on soil brightness. Furthermore, soil-induced greenness changes became greater with increasing amounts of vegetation up to 60% green cover. The results presented suggests that soil and plant spectra interactively mix in a nonadditive, partly correlated manner to produce composite canopy spectra.

Ezra, C. E., Tinney, L. T., and Jackson, R. D. Effect of soil background on discrimination of vegetation using Landsat data. Remote Sensing of Environ., 16:233-242.

Landsat satellite digital count values were extracted from a 512 by 512 subscene for wet and dry bare soil points over three spectrally different soil types. These values were used to calculate brightness and greenness values for the three site specific soils using a set of global coefficients. A comparison was made between the use of global coefficients and those derived for individual soil types. Results showed

that the effect of soil background noise in the discrimination of vegetation can be more effectively minimized using site specific soil lines. This technique enhances the potential for remotely sensed data to be used for smaller area assessments such as individual fields.

Dusek, D. A., Jackson, R. D., and Musick, J. T. Linear correlations between winter wheat parameters and various combinations of seven spectral bands. Remote Sensing of Environment. (Not yet accepted).

Reflectance data were taken for a full growing season on six varieties of winter wheat grown over a range of water deficit treatments (controlled by irrigation) in the Southern High Plains. Spectral data were collected with a multiband modular radiometer having seven bands within the reflected region of the spectrum. A total of 660 vegetation indices were formed and linearly related to five parameters of winter wheat. Indices derived were of two types, ratios and linear combinations (n-space). Ratio vegetation indices produced higher r^2 values for four wheat parameters; leaf area index, green ground cover, total wet and total dry phytomass, whereas, n-space greenness indices were more highly correlated to leaf phytomass. Highest correlation coefficients were .83 to .85 for ratio indices and equations indicate good prediction for a range of data involving water deficits and varieties of winter wheat.

CANOPY TEMPERATURE

Idso, S. B., Reginato, R. J., Clawson, K. L., and Anderson, M. G. On the stability of non-water-stressed baselines. Agric. for Meteorol. 32:177-182.

Non-water-stressed baselines--plots of foliage-air temperature differential vs. air vapor pressure deficit--were obtained for seven different varieties of wheat and one variety of water hyacinth having three different characteristic leaf sizes in experiments conducted at Phoenix, Arizona. A single baseline was found to describe adequately the data for all seven wheat varieties; while three different baselines were required for the three different leaf-sized canopies of water hyacinth. The slopes of the three water hyacinth baselines were all identical; however, their intercepts differed by as much as 6°C.

Idso, S. B., Pinter, P. J., Jr., Reginato, R. J., and Clawson, K. L. Stomatal conductance and photosynthesis in water hyacinth: Effects of removing water from roots as quantified by a foliage-based plant water stress index. Agric. for Meteorol., 32:249-256.

Stomatal conductance and net photosynthesis measurements were made over a period of a week in mid-October on two stands of water hyacinths floating in sunken metal stock tanks at Phoenix, AZ. On the second day of the experiment, all free water in one of the tanks was removed. Foliage temperature measurements were subsequently used to quantify the water stress experienced by the water-robbed plants; and a plant water

stress index derived from the foliage temperature and air vapor pressure deficit data was used to study the effects of developing water stress on the plant physiological parameters being measured. The results obtained were practically identical to those derived from two independent season-long studies of water stress effects in cotton: net photosynthesis decreased linearly to become negative at a plant water stress index of 0.9 (where 1.0 represents the maximum possible stress), while a parameter related to plant water use efficiency first increased with increasing stress to reach a maximum at a plant water stress index of 0.6, after which it dropped off rapidly to zero with additional stress.

Choudhury, B. J., and Idso, S. B. Simulating sunflower canopy temperatures to infer root-zone soil water potential. Agric. for Meteorol., 31:69-78.

A soil-plant-atmosphere model for sunflower (Helianthus annuus L.) together with clear sky weather data for several days, was used to study the relationship between canopy temperature and root-zone soil water potential. Considering the empirical dependence of stomatal resistance on insolation, air temperature and leaf water potential, a continuity equation for water flux in the soil-plant-atmosphere system was solved for the leaf water potential. The transpiration flux was calculated using Monteith's combination equation, while the canopy temperature was calculated from the energy balance equation. The simulation showed that, at high soil water potentials, canopy temperature is determined primarily by air and dew point temperatures. These results agree with an empirically derived linear regression equation relating canopy-air temperature differential to air vapor pressure deficit. The model predictions of leaf water potential were also in agreement with observations, indicating that measurements of canopy temperature together with a knowledge of air and dew point temperatures can provide a reliable estimate of the root-zone soil water potential.

CO_2, AGRICULTURE AND CLIMATE

Idso, S. B., Kimball, B. A., and Clawson, K. L. Quantifying effects of atmospheric CO_2 enrichment on stomatal conductance and evapotranspiration of water hyacinth via infrared thermometry. Agric. of Meteorol., 33:15-22.

Measurements of stomatal conductance and evaporative water loss from two tanks of water hyacinths growing at Phoenix, AZ, one under ambient conditions and one considerably enriched in atmospheric CO_2, are reported. Stomatal conductances of plants in the CO_2-enriched treatment were reduced to values half as great as those of plants in the ambient treatment at a mean mid-day CO_2 concentration of 550 ppm, which resulted in a 22% decrease in total evaporative water loss; while in going from an ambient CO_2 concentration of 310 ppm to a doubled concentration of 620 ppm there was a 27% decrease in evaporative water loss. Both of these physiological responses were characterized by the Idso-Jackson plant water stress index. Additionally, it was found that the stomatal

response to increasing atmospheric CO_2 was identical to those induced by removing water from the plant roots, and that the reduction in evaporative water loss with increasing atmospheric CO_2 was an inverse linear function of the plant water stress index--both of which phenomena had previously been theorized but never before experimentally verified.

Idso, S. B. An empirical evaluation of Earth's surface air temperature response to radiative forcing, including feedback, as applied to the CO_2-climate problem. Arch. Meteorol. Geophys. Bioclim., Ser. B, 34:1-19.

Several natural experiments were analyzed to yield equilibrium values of a surface air temperature response function and a feedback factor for Earth's atmosphere. The former parameter, the change in surface air temperature induced by a change in radiant energy absorbed at the surface was demonstrated to have a value of about 0.1 K $(Wm^{-2})^{-1}$; while the latter parameter, the ratio of feedback-induced change in radiant energy to the surface of the Earth divided by an initial or primary change in radiant energy to the Earth's surface was demonstrated to have a value of about 1.25. These two numbers imply that the maximum warming to be expected from a doubling of Earth's atmospheric CO_2 concentration from 300 to 600 ppm is only about 0.1 K, a result so small as to possibly be completely counter-balanced by the CO_2-induced reduction of solar radiation transmission to the Earth's surface.

Idso, S. B. What if increases in atmospheric CO_2 have an inverse greenhouse effect? I. Energy balance considerations related to surface albedo. J. Climatol. 4:399-409.

An analysis of northern, low and southern latitude temperature trends of the past century, along with available atmospheric CO_2 concentration and industrial carbon production data, suggests that the true climatic effect of increasing the CO_2 content of the atmosphere may be to cool the Earth and not warm it, contrary to most past analyses of this phenomenon. A physical mechanism is thus proposed to explain how CO_2 may act as an inverse greenhouse gas in Earth's atmosphere. However, a negative feedback mechanism related to a lowering of the planet's mean surface albedo, due to the migration of more mesic-adapted vegetation onto arid and semi-arid lands as a result of the increased water use efficiency which most plants experience under high levels of atmospheric CO_2, acts to counter this inverse greenhouse effect. Quantitative estimates of the magnitudes of both phenomena are made, and it is shown that they are probably compensatory. This finding suggests that we will not suffer any great climatic catastrophe but will instead reap great agricultural benefits from the rapid increase in atmospheric CO_2 which we are currently experiencing and which is projected to continue for perhaps another century or two into the future.

Idso, S. B. Atmospheric CO_2 variability: A cause for concern in the reconstruction of past climates. Spec. Sci. Tech. 7:37-40.

Well documented effects of atmospheric CO_2 on plant water use efficiency were shown to have the capacity to significantly influence the floristic

composition of natural plant communities, as well as their distributions in space and time. This phenomenon, previously overlooked in the reconstruction of past climates, may be introducing large errors into our interpretation of several paleoclimatic indicators. Indeed, it is very possible that much of our understanding of Earth's climatic history is distorted, due to previously ignored direct and indirect effects of atmospheric CO_2 variability.

Idso, S. B. and Brazel, A. J. Rising atmospheric carbon dioxide concentrations may increase streamflow. Nature 312:51-53.

Historically, studies of the greenhouse effect on carbon dioxide (CO_2) have dealt primarily with temperature and secondarily with precipitation. In the latest report on this topic produced by the U.S. National Research Council, however, the subject of streamflow is broached with an analysis which suggests that watershed in the western United States will suffer 40 to 75% reductions in streamflow for a doubling of the atmospheric CO_2 content which leads to a 2°C rise in air temperature and a 10% drop in precipitation. A shortcoming of this study is that it does not include the direct antitranspirant effect of atmospheric CO_2 enrichment, whereby increasing the CO_2 content of the air tends to induce partial stomatal closure which reduces plant transpiration and thereby conserves soil moisture and increases runoff to streams. Inclusion of this latter effect in a simple model of watershed runoff applied to 12 drainage basins in Arizona indicates that 40 to 60% <u>increases</u> in streamflow will be the likely consequences of a CO_2 concentration doubling, even in the fact of adverse changes in temperature and precipitation.

TRANSPIRATION BY AQUATIC VEGETATION

Anderson, M. G. and Idso, S. B. Evaporative rates of floating and emergent aquatic vegetation: Water hyacinths, water ferns, water lilies and cattails. Proc. Amer. Meteorol. Soc. Seventh Conf. Biometeorol. and Aerobiol. and 17th Conf. Agric. and Forest Meteorol. (In press)

The possibility of reducing evaporative water losses from ponds and reservoirs was investigated using several different-sized ponds of water hyacinths, water ferns, water lilies and cattails. Similar-sized ponds devoid of vegetation provided the basis of comparison for isolating the effects of the different types of vegetation, while daily water level measurements provided the basis of water loss assessment. The flat, floating species--water ferns and water lilies--always reduced evaporation below that of identical open water surfaces, as did <u>short</u> water hyacinths on <u>large</u> ponds. For cattails and <u>tall</u> water hyacinths, however, there was generally a modest increase in evaporative water loss. Nevertheless, for large ponds the enhancement of evaporation rate was so small that removal programs to rid reservoirs of these plants based on water conservation arguments are probably not cost effective.

CO_2 AND PLANTS

An experimental program was initiated this year to study the effects of atmospheric CO_2 enrichment on growth and transpiration of water hyacinths and desert agaves, as well as to look for possible growth effects in populations of fresh-water algae. Analyses of this first year's data are still in progress and will thus have their discussion deferred until next year's report. Consequently, we will here only describe the basis of the experimentation.

Four clear-plastic-wall, open-top, field, CO_2-enrichment chambers were constructed as shown in Fig. 1. One of these chambers was enriched to approximately 900 ppm CO_2, one to 650 ppm, one to 500 ppm and one used as an ambient control. One tank in each chamber had water hyacinths growing in it, while the other was filled with a mixture of fresh-water algae selected for potential high protein production. Individually potted agave plants were positioned around the inner peripheries of each chamber.

Daily evaporative water losses from each chamber were obtained by means of stilling wells connected to each sunken metal stock tank. Weekly fresh weight production by the water hyacinths was determined by physically lifting the plants out of the water and weighing them. For this purpose, each tank had submerged within it an epoxy-coated wire-mesh basket of the design shown in Fig. 2 which was lifted out of the water by the technique depicted in Fig. 3. Optical density measurements were used to study the productivity of the algae; while initial dry weights of the agave transplants provided a basis for later determinations of their growth response to the CO_2 treatments.

Experiments of this nature with this setup are expected to continue for at least two more years.

NET RADIOMETERS

Net radiometer calibration is a frequent duty faced by many micrometeorologists. Accurate calibration of these instruments is vital to the calculation of energy balance equations. Of all of the various calibration techniques available, the occulting technique is the easiest and least expensive to use. The effect of the underlying surface (whether vegetated or not) on the calibration coefficient using the occulting calibration technique has not been previously reported. The purpose of this study was to determine if such an effect exists and how large that affect might be.

The experiment was conducted on 16 and 17 May 1984 in the lysimeter field of the U.S. Water Conservation Laboratory. On the two study days, nine Fritschen net radiometers were mounted on a rack at a height of 1 m as shown in Fig. 1. A Eppley Model 15 pyranometer calibrated as a laboratory standard against the National Oceanic and Atmospheric Administration standard, was also mounted on the stand. The occulting calibration technique was employed by placing a 25 cm^2 occulting square at a height of 50 cm above each radiometer. The radiometers were alternately shaded or unshaded, with the voltage output of each sensor

recorded after 3 minutes of equilibration with a Omnidata Model 516-B polycorder. Measurements began at 1100 and ended at 1430 MST, thereby providing a bracket about solar noon, which occurred at 1225 MST. Calibrations were performed over a bare soil surface on the first day and over an alfalfa canopy on the second day. The alfalfa canopy was about 50 cm tall and ground cover was 100% complete. A paired t-test was employed to compare the two data sets.

Weather conditions for both days were nearly identical and are given in Table 1. Direct comparison of the calibration coefficients obtained on the two days should not, therefore, be affected by different weather conditions.

The calibration coefficient together with the standard deviation of the coefficient for each net radiometer is listed in Table 2. The difference between the two calibrations, using bare soil as the reference surface, is also given. The difference in coefficients indicated that 89% of the net radiometers showed a higher coefficient (greater sensitivity) when calibrated over the bare soil surface. The overall average difference for all net radiometers was, however, only 0.99 $W\ m^{-2}\ mV^{-1}$. A paired t-test of this difference indicated that the average difference in coefficients was not large enough to be significant statistically at $\alpha = 0.05$. The difference of 0.99 $W\ m^{-2}\ mV^{-1}$ is also much less than the average standard deviation for each coefficient (3.40 $W\ m^{-2}\ mV^{-1}$) further indicating the lack of surface affects on the calibration coefficients.

The conclusion to be drawn from these data is that net radiometer calibration coefficients, calculated using the occulting technique, are not affected by the surface over which the calibration is conducted. Care should nevertheless be exercised during calibration to ensure that terrestrial radiation from the surface remains constant. If this component of the net radiation is not constant from shaded to unshaded conditions, the coefficients may be seriously affected.

REMOTE IMAGE PROCESSING SYSTEM

The Remote Image Processing System (RIPS) is a recent acquisition of our laboratory and consists of the following components:

1) Cromemco 64K, 8-bit processor;
2) Black and white printer;
3) Color and black and white monitors;
4) Joystick, and
5) Image processing software.

The system is currently being used for digital image display, enhancement and classification. Development is currently underway to enhance the RIPS to perform binary and ASCII file transfer with the HP-1000 mainframe computer. With this down loading capability, the RIPS will be used for image-based agricultural modeling, such as spatially continuous evapotranspiration calculation, biomass estimation and change detection over time and space.

ALFALFA 84

In 1984, we planted an Arizona adapted, non-winter hardy cultivar of alfalfa (Medicago sativa L. cv. Lew) in the backyard lysimeter field at the U.S. Water Conservation Laboratory in Phoenix. In addition to providing a perennial crop on which we could conduct our remote sensing research, a long term alfalfa rotation was intended to improve soil structure, fertility and organic matter as well as reduce potential disease problems which were beginning to surface after 6 continuous years of small grain cultivation.

OBJECTIVES

Our primary objectives for this experiment continue to focus on developing and refining remote sensing approaches for the early detection and quantification of various plant stresses. Alfalfa is an ideal crop to study because of its year round growth in central Arizona, up to 8 harvest events per year and the fact that much time is spent under partial canopy cover conditions. The latter is of special interest because we saw an urgent need to address the partial canopy problem as it influences various remote sensing measurements. A specific goal within this experiment is to evaluate a combination remote sensing technique for estimating evapotranspiration of alfalfa in situations wherein varying amounts of plant cover and seasonal differences in plant transpiration might complicate the procedure.

Additional objectives are to further develop thermal and reflective solar remote sensing measurements as techniques which could be used by researchers and growers to assess physiological stresses and biomass levels in the field. Such tools would have a tremendous impact on the ability to quantify stress with time and estimate its effect on final yield. Our intent is to establish the non-destructive remote sensing methods as reliable surrogates for many of the conventional sampling methods which are labor intensive, difficult, destructive and more subject to sampling errors because they are point measurements. Within this objective we expect to better define weather conditions under which measurements yield acceptable results and establish the effect of viewing angle on the response of portable infrared thermometers.

Vegetation indices derived from the reflectance of light from plant canopies can be used to infer the history of stresses to which a crop has been exposed as reflected in varying amounts of biomass accumulation or senescence. In this experiment we also wished to establish whether reflectance measurements could be used unambiguously to identify stress as it is developing in the field and to provide an early warning signal much in the same way the thermal IR is used in the Crop Water Stress Index.

CULTURAL PRACTICES

Experimental plots were fertilized with treble super phosphate (0-45-0) at a rate of 100 kg/ha. This was then incorporated into the soil by rototilling to a depth of 10-15 cm. One week later on 14 Feb 85 we planted the alfalfa seed in 18 separate borders at a recommended rate of about 46 kg/ha. The field was dragged lightly to settle the seed in the upper layers of the soil. An initial irrigation was given on 14-17 February and first germination occurred on 21 February. A second irrigation was given on 21-23 February to reduce soil crusting and insure good emergence. In 1984, we harvested the alfalfa stand a total of 6 times (21 May, 23 June, 25 July, 21 August, 25 September, and 15 November.

IRRIGATION TREATMENTS

All borders were irrigated at the same time and kept well watered by surface irrigation until after the fourth harvest on 21 August. This insured that plants were well established before we began differential water stress treatments. For the fifth and subsequent harvest cycles we followed a rotation system of irrigations to provide differential stress while minimizing carry-over effects of prior stress on plant response. Experimental plots exposed to water stress during a particular harvest cycle would have two subsequent cycles under well-watered conditions before they were once again exposed to stress.

Two replicates of 4 irrigation treatments were established for each cutting interval. A WET treatment would experience no appreciable water stress between cuttings. An EARLY irrigation treatment would be irrigated within several days following harvest and then experience water stress during the later stages of canopy development. A LATE treatment would experience water stress during canopy regrowth but have ample water later in the harvest cycle. Finally, a DRY treatment would have no supplemental water added by irrigation from one harvest until the next. The DRY plots' only source of moisture would be rainfall and stored soil moisture. Non-treatment plots received ample water (same as the wet treatment) during their two cycle recovery period. The shortest time period between harvests during the summer months was approximately 4 weeks. During that time the wet plots received 2 irrigations; the early and late plots, 1 irrigation; and the dry plots, no irrigation. Irrigation amounts for the wet, late and non-treatment plots were adjusted to replenish the water used in the upper 150 cm of soil as measured by a neutron scattering technique; that in the early treatment was replenished only to a depth of 90 cm to insure that it would experience some stress before the next harvest.

MICROMETEROLOGICAL OBSERVATIONS

Micrometeorological measurements were modeled after those employed in previous experiments and included standard measurements of global solar radiation, diffuse solar radiation, rainfall, wind speed and direction,

etc. Six borders of alfalfa were instrumented to record reflected solar radiation, net radiation, wet and dry bulb temperatures and soil temperatures at a 5 cm depth. Two borders contained thermocouples for monitoring air and soil temperature profiles and 3 soil heat flux plates at a depth of 5 cm. One wind speed profile was obtained in a central location within the experimental field. The three lysimeters located in the field were each instrumented with a nadir-pointing infrared thermometer, a soil heat flux plate and soil thermocouples buried at depths of "0," 1, 2, and 5 cm. Directly wired shorts and 0°C temperature references from an electric ice point device provided a means by which temperature-induced signal drift in the emf and thermocouple response could be correctly compensated.

Micrometeorologial data were scanned at 1.5 minute intervals by an Autodata-9 data logger and two remote scanners. Table 3 provides a list of measurements and channel assignments for this experiment. At 30-minute intervals the time averaged channel observations were sent to an HP-9836 desktop computer and then relayed to the laboratory HP-1000 minicomputer. A Winchester hard disk, hard wired to the HP-9836 was used to backup the data sent to the HP-1000. Upon demand, the most recent processed data could be printed out via the HP-9836. Lysimeter data were recorded from 15 February until 25 June 84. Most of the remaining instruments were installed in the field and recording began 24 August 84.

AGRONOMIC PARAMETERS

Plant heights were measured in the field 3 times weekly. Nadir and oblique color photographs were taken once a week. Destructive samples were obtained from each of the treatment plots 3 times a week from August until late October. As plant growth slowed during the cooler months, the sampling frequency was decreased to twice and then once a week. Destructive samples consisted of 4 circular, 0.25 m^{-2} samples per plot. Plants were clipped at a height of approximately 3 cm. Plant material was weighed immediately after sampling, green and brown fractions were separated and then oven-dried for a minimum of 48-72 hours at 50-60 C. Dry biomass was measured for each fraction.

SOIL WATER

Soil water depletion was measured 3 times a week using a neutron scattering technique. Most plots were measured to a depth of 260 cm in 20-cm increments. Upper and lower limits of plant extractable water had been established for each layer in individual plots during previous experiments. After differential moisture treatments were begun in August 84, we deemed it advisable not to change these limits midway through the experiment because of suspected differences in rooting patterns between treatments. Upper and lower limits will be adjusted at the end of the experiment with the best data then available for the alfalfa crop. Depleted soil moisture information was used to determine irrigation amounts. Surface soil moisture was sampled at appropriate intervals in several of the plots using an Oakfield probe. These data were used to determine soil heat flux during late fall and winter months.

LEAF DIFFUSION RESISTANCE

Leaf diffusion resistance measurements were taken at intervals during the experiment using a LICOR-1600 steady state porometer. Data were collected from 3 upper and 3 lower leaf surfaces from each treatment plot during daily periods of maximum water stress (1300-1400).

REMOTE SENSING OBSERVATIONS

Reflected solar radiation was monitored using two portable multiband radiometers. The first, an Exotech Model 100-A, was equipped with 2 visible and 2 near-infrared wavebands similar to those of the LANDSAT Multispectral Scanner (MSS). It was handheld over the experimental plots at the time when the solar zenith angle was approximately 57°. Data were collected almost daily beginning on 27 August 84 under clear and cloudy sky conditions. Reflectances were computed as the ratio of radiances measured each experimental plot to the time-interpolated irradiances inferred in the waveband interval from measurements over a calibrated, painted $BaSO_4$ reference panel. An example of a vegetation index calculated as the ratio of Exotech band 4 (NIR) to band 2 (Red) is shown in Fig. 4. At intervals the Exotech radiometer and other remote sensing instruments were employed intensively on a diurnal basis.

A second radiometer, a Barnes Multimodular Radiometer (MMR) was mounted on a backpack device and deployed over the alfalfa plots on clear days only. Data were collected at a time corresponding to the approximate overpass of Landsat 5 (1030 h). The MMR had waveband filters which mimic those of the visible, near-IR, mid-IR and thermal channels of the Thematic Mapper Radiometer. It also has an additional near-IR channel which is proportedly sensitive to liquid water in plant tissues and thus should be useful in the monitoring of plant stress.

Thermal infrared measurements of the alfalfa canopies were made at approximately 1330 to 1400 h 5 days a week using an Everest portable IRT with nominal 4°FOV optics. Canopies were viewed from each of the 4 cardinal compass directions as well as in a nadir direction.

PERSONNEL: R. J. Reginato, R. D. Jackson, S. B. Idso, P. J. Pinter, Jr., K. L. Clawson, C. E. Ezra,, M. S. Moran, R. S. Seay, S. M. Schnell, H. L. Kelly, Jr., B. L. Carney, S. M. Karpinski, B. L. Murphy, P. Barrett.

Table 1. Summary of weather conditions on 16 and 17 May 1984.

DAY	AVG. DRY BULB (C)	AVG. WET BULB (C)	AVG. DIRECT BEAM SOLAR RADIATION* (Wm^{-2})	WIND SPEED** (m/s)	WIND DIRECTION** (DEGREES)	SURFACE
16 MAY	32.6	17.5	837.6	2.3	174	BARE SOIL
17 MAY	31.7	18.7	848.2	2.2	176	ALFALFA

*Calculated from the alternately shaded and unshaded standard pyranometer.

**Campbell Scientific CR-21 Micrologger data at 2 m height located in the lysimeter field.

Table 2. Calibration coefficients (W m^{-2} mV^{-1}) of net radiometers determined over a bare soil and an alfalfa surface. The uncertainty of the calibration coefficient is the standard deviation of 33 independent calculations.

	SERIAL NUMBERS								
	620	654	655	680	682	692	693	694	705
BARE SOIL									
COEFFICIENT	215.8	243.1	265.0	258.8	235.7	221.4	225.5	222.3	222.0
UNCERTAINTY	3.36	3.24	4.03	3.60	3.58	2.69	3.66	2.85	3.56
ALFALFA									
COEFFICIENT	214.6	243.5	263.4	255.6	235.2	220.5	225.3	220.7	221.9
UNCERTAINTY	1.79	3.83	2.27	4.22	2.32	0.88	2.79	2.56	2.25
DIFFERENCE IN COEFFICIENTS	1.2	-0.4	1.6	3.2	0.5	0.9	0.2	1.6	0.1

Table 3. Instrumentation for Alfalfa 84.

Parameter	Location	Height	Channel Number	Instrument Mfg.	Installation Date	Signal Level
Albedo	1B	1.5 m	003	Spectran	237	mV
	2B		004			
	3B		005			
	4B		103			
	5B		104			
	6B		105			
Net radiation	1B	1.5 m	013	Micromet	237	mV
	2B		014			
	3B		015			
	4B		113			
	5B		114			
	6B		115			
Soil Heat Flux	2B	-50 mm	020	Micromet	237	mV
			021			
			022			
	3B		023		276	
			024			
			025			
	Lys. 1		026		237	
	Lys. 2		027			
	Lys. 3		120			
Wind Speed	2B	0.75 m	045	Young	237	V
		1.00 m	044			
		1.25 m	043			
		1.50 m	042			
		1.75 m	041			
		2.00 m	040			
	4B	2.00 m	122			
Nadir Canopy Temp.	Lys. 1	1.75 m	032	Everest 15°FOV	237	V
	Lys. 2		033			
	Lys. 3		121			
Within Canopy Air Temp.	2B	0.1 m	050	Thermocouple	237	C
		0.2 m	051			
		0.3 m	052			
		0.4 m	053			
		0.5 m	054			
		0.6 m	055			
		0.7 m	056			
		0.8 m	057			
		0.9 m	058			
	3B	0.1 m	130		276	C
		0.2 m	131			
		0.3 m	132			
		0.4 m	133			
		0.5 m	134			
		0.6 m	135			
		0.7 m	136			
		0.8 m	137			
		0.9 m	138			
Soil Temp. Profile	2B	0 mm	066	Thermocouple	237	C
		-10 mm	067			
		-20 mm	068			
		-50 mm	070			
	3B	0 mm	071		276	
		-10 mm	072			
		-20 mm	073			
		-50 mm	074			
	Lys. 1	0 mm	075		237	
		-10 mm	076			
		-20 mm	077			
		-50 mm	078			
	Lys. 2	0 mm	080			
		-10 mm	081			
		-20 mm	082			
		-50 mm	083			
	Lys. 3	0 mm	150			
		-10 mm	151			
		-20 mm	152			
		-50 mm	153			
Dry Bulb	1B	1.5 m	060	Psychrometer	237	C
	2B		062			
	3B		064			
	4B		140			
	5B		142			
	6B		144			
Wet Bulb	1B	1.5 m	061	Psychrometer	237	C
	2B		063			
	3B		065			
	4B		141			
	5B		143			
	6B		145			
Soil Temp.	1B	-50 mm	093	Thermocouple	237	C
	2B		094			
	3B		095			
	4B		163			
	5B		164			
	6B		165			

Table 3. (Cont.) Instrumentation for Alfalfa 84.

Parameter	Location	Height	Channel Number	Instrument Mfg.	Installation Date	Signal Level
Nadir IRT Shield Temp.	2B	1.5 m	084	Thermocouple	237	C
East Scanner Temp.	4B	1.5 m	158	Thermocouple	237	C
West Scanner Temp.	2B	1.5 m	088	Thermocouple	237	C
Cabin Temp.	Cabin	1.5 m	228	Thermocouple	237	C
Global Radiation	Cabin	Roof	200	Eppley	237	mV
Diffuse Radiation	Cabin	Roof	201	Eppley	237	mV
PAR	Cabin	Roof	202	LICOR	237	mV
Baro-metric Pressure	Cabin	0.5 m	203	Sierra Misco	237	mV
Windspeed	Cabin	Roof	204	Gill	237	V
Wind Direction	Cabin	Roof	205	Gill	237	V
Fullscale	Cabin	Roof	206	Gill	237	V
Zero	Cabin	Roof	207	Gill	237	V
Lysimeter	2B	—	210	--	237	mV
	3B	—	211	--	237	mV
	4B	—	212	--	237	mV

Water Hyacinth–Carbon Dioxide Enrichment Chamber/Clear Plastic
1/40 Scale

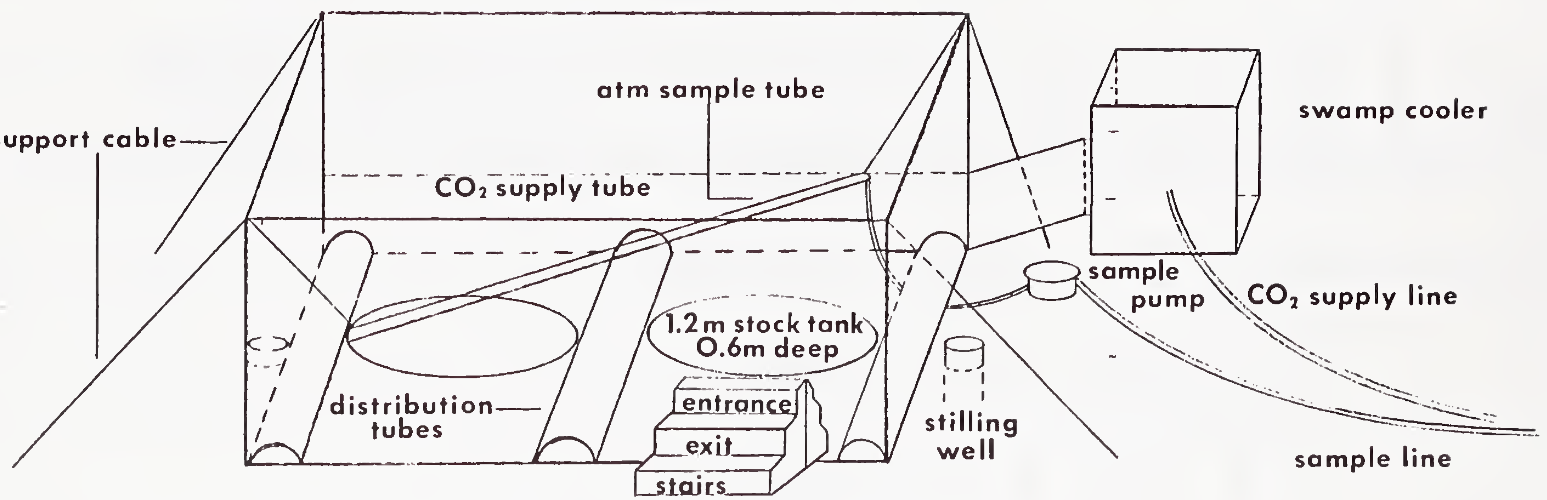


Figure 1.

Water Hyacinth-Carbon Dioxide Enrichment Study

Weighing & Growth-Basket Design

Aluminum Framed 1/20 Scale

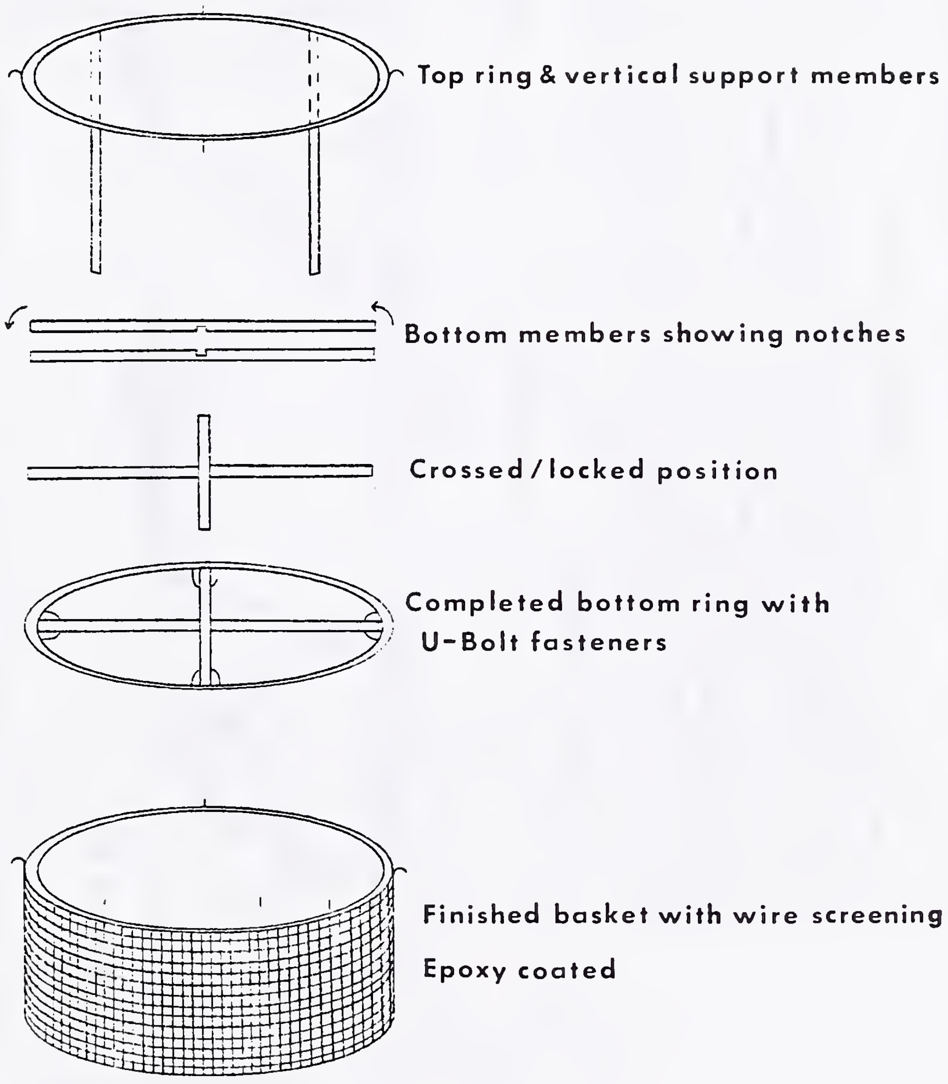
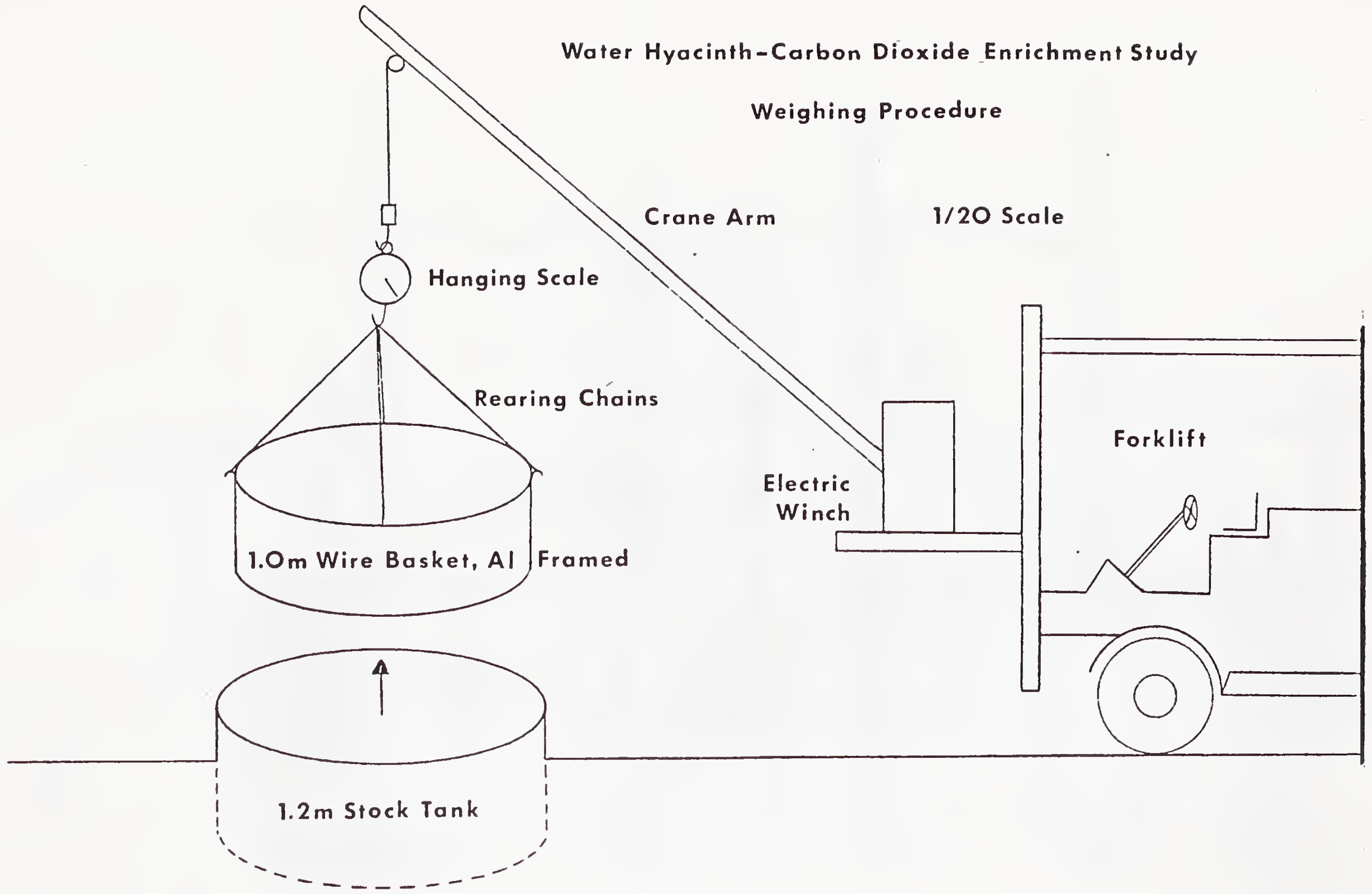


Figure 2.



Water Hyacinth-Carbon Dioxide Enrichment Study
Weighing Procedure
Crane Arm
1/20 Scale
Hanging Scale
Rearing Chains
Forklift
Electric Winch
1.0m Wire Basket, Al Framed
1.2m Stock Tank

Figure 3.

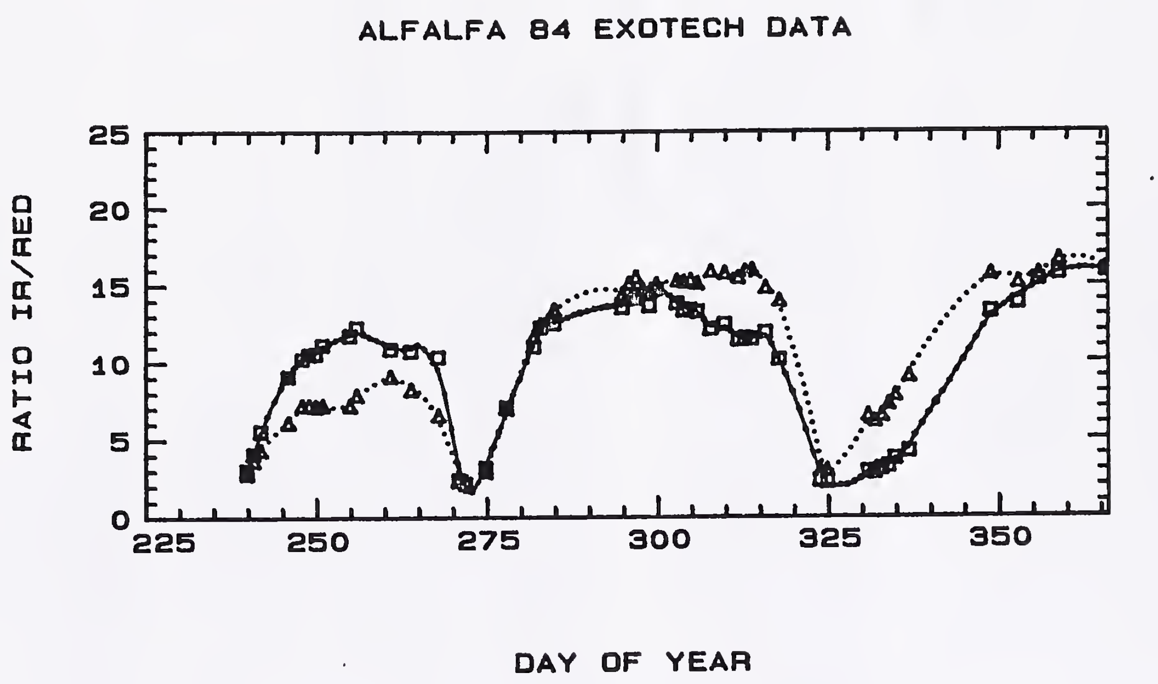


Figure 4. Daily values of a Vegetation Index calculated as the ratio of near-IR to Red light reflectances measured with the Exotech Radiometer are shown for two alfalfa plots in 1984. Plot 2A (dotted line) was a dry treatment during the first harvest cycle. Plot 3C (solid line) experienced a dry treatment during the second harvest cycle. The data shown in this figure were collected under conditions when the direct beam solar radiation was unobstructed by clouds and the sun was at a solar elevation of 33°.

TITLE: SOIL-WATER-PLANT RELATIONSHIPS OF DROUGHT-TOLERANT CROPS IN ARID ENVIRONMENTS

NRP: 20760 CRIS WORK UNIT: 5510-20760-002

INTRODUCTION:

This research has had two overall objectives: (1) to increase the productivity of arid and semiarid lands using runoff farming (RF) and in the process (2) to introduce new, high-value, low water requiring crops to these water-short areas. Meeting objective (1) has entailed laboratory research to develop high-runoff-efficient, inexpensive and durable water harvesting treatments for the catchments portion of the RF system, and field research to develop the complete system with treated catchments, crops and all the associated agronomic practices. We have worked primarily with two crops to meet objective (2): jojoba and Christmas trees. We concluded that jojoba was not a good crop for RF in arid areas receiving summer rains, but might be a good choice for areas with a Mediterranean climate.

Recently, we have been evaluating conifers for RF. This crop was designated for Christmas trees. We found that we could sucessfully grow commercially acceptable Christmas trees for some tree species-RF system-soil combinations, but not for others. In 1984, we initiated research to eliminate this uncertainty, and to develop cultural techniques to reduce tree mortality, speed growth and improve quality.

RESEARCH APPROACH:

In the laboratory, several tallow-derivative materials supplied by the ARS Eastern Regional Research Center were combined with additives, applied to soils and evaluated for repellency and weatherability using previously developed testing procedures.

The water repellent materials evaluated included the following list of tallow derivatives and mixtures of them with paraffin -131AMP and 140 slack wax:

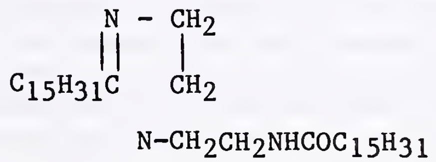
AF 729-82 $RC{=}NCH_2CH_2N{-}CH_2CH_2NHCOR$

N-(2-Tallow Δ^2 imidazoline)ethyl Tallowamide

AF 729-84 $RCONHCH_2CH_2N(COR)CH_2CH_2NH_2$

N-(Aminoethyl)N-Tallow amido ethyl Tallowamide

AF 706-69-I



N-2(pentadecyl Δ^2 imidazoline)ethyl stearamide

AF 706-74 II $C_{15}H_{31}CONHCH_2CH_2NHCH_2CH_2NHCOC_{15}H_{31}$

Dipalmitamidoethyl Amine

Samples were prepared using the following sequence:
150 g air dry <2 mm Granite Reef soil per 9 cm diameter

Petri dish bottom; smooth soil; wet with 15 g distilled water applied with an atomizer; cover; equalibrate overnight; compact (5 blows with standard compactor); air dry; treat with cellulose xanthate (10 ml/dish of 0.4% cellulose solution applied with atomizer); air dry; brush on wax-antistrip mixture; melt into soil with heat lamps; treat petri dish edges with melted mixture of 2/3 160 M.P. paraffin, 1/3 Vaseline. Treatments were prepared in duplicate.

The samples then were evaluated using the alternating weathering-testing procedure:

```
     4-hr-hydration (+ or - for pass-fail)
         ↓
     erosimeter(1 mm water jet at 5 psi for 5 min)
         ↓
  |  freeze-thaw cycling(±20° with approx. 2.5 cm diameter
  |       water drop atop center of each sample)
  n      ↓
  |  erosimeter
  |      ↓
  |  4-hr-hydration
```

The erosimeter was run at 5 psi for n=1 through 40; then at 15 psi on surviving samples until failure.

At the Camp Verde field test site 4 studies were in various stages of progress: (1) the study of the original planting of two tree species at two sites (clay and sand) and associated stump-culture evaluation was concluded, (2) the first study on combining RF with drip irrigation continued, as did (3) the evaluation of cloning to improve tree properties and reduce variability, and (4) a new study was initiated to improve early growth, rooting properties and quality of the Elarica Pine. Installation procedures for the first three studies appear in earlier annual reports.

For study (4), the "sandy" runoff-farming site at Camp Verde was replanted entirely to Eldarica pine in 1984. Prior to planting, the site was clear-cut and each of the six terraces randomly divided into five tillage treatments: (1) controls, (2) tillage to depth of 3 feet, (3) no. 2 with inclusion of pine duff residues, (4) no. 2 with inclusion of a silty loam soil, and (5) planting a known deep-rooting species along with the pine. Tillage was an auger hole drilled and refilled adjacent to each planting site. There also was a new (previously unplanted) row of trees with the five tillage treatments. Two trees were planted per site; the smaller of the two trees was to be removed after the first growing season. A drip system was installed to water

the trees weekly from planting in March until the start of the summer rainy season.

RESULTS:

Laboratory:

Results for the evaluation of the tallow derivative-petroleum-base wax water repellents are shown in Table 1. Generally, the tallow-wax mixtures were considerably more stable than either component alone. The Emery antistripping agent markedly improved the weatherability of the petroleum base waxes, but its effects were inconsistent with the tallow materials.

Field:

Table 2 is a summary of the harvestable trees from the two successful tree-treatment combinations of field study 1. Shown is the disposition of the original and the associated first crop of stump-cultured trees. It was hoped that the stump cultured trees could be matured a year or two sooner than the originals, thus markedly shortening the harvest cycle time.

Almost 90% of the cypress seedlings on the sand site reached marketable size in only 3 years, but stump culturing was completely unsuccessful. For the cypress, we had to be content with 0.3 salable trees per spot per year using the three year cycle.

We had better success stump culturing the pine on the clay site. At the end of 6 years we had harvested 96% of the original planting, plus another 77% as stump cultured trees, or a total of 173% of the original planting. This amounts to 0.29 salable trees per planting spot per year, or nearly one tree per spot every three years. For comparison, in northern climates, 5 to 10 years are normally required to mature a Christmas tree, or less than 0.1 to 0.2 trees per spot per year.

Results of the first drip irrigation study at Camp Verde (study 2) for starting conifer seedlings on an RF system were mixed: the automatically timed system eliminated hand watering during establishment, but did not hasten maturity or reduce mortality. Apparently, as in study 1, the trees had difficulty rooting into the dense, sandy soil. We also tried some trimming on these trees, and late season application of nitrogen to improve color at cutting time.

The "Clemson Greenspire" cuttings (study 3) present a very uniform stand after two growing seasons, which shows that this technique can be used to improve tree quality, and possibly rate of growth and other desirable characteristics. However, this selection of Arirzona cypress, which is suitable for conditions in South Carolina, is not well adapted to the harsh conditions of RF at Camp Verde. Future selections for cloning must be made locally from existing RF sites.

For study 4, the average height, (best of two trees per planting site) after the first growing season of all the replanted trees on the old RF

(study 1) site, was 43 cm. The seedlings nearly tripled their height this first year. This also is three times the first year's average growth of the first Eldarica planting at the site (28 vs. 9 cm, respectively). Average growth (best of two trees/site) of the trees on the single newly planted row was only 13 cm, or only slightly better than that of the first study. It is too early to try to relate growth to the five tillage treatments. It was during the second and third summers in studies 1 and 2 that we experienced the high mortality of the pine on the sand site. However, the vigorous top growth suggests that this new planting has already rooted deeply, and because of the fast start, the trees could reach marketable size in only 3 years.

The drip system ran until mid-August and applied 104 gal/tree site. This calculates out to be only 3.4, 2.3, and 1.7 inches of irrigation water for the combined growing and catchment areas of the three sized terraces in the study. Most of the collected runoff this first year was deep percolated. Undoubtedly, this was many times that small amount removed by the irrigation system.

The RF studies were terminated during 1984 and the sites are being restored.

PERSONNEL: Dwayne H. Fink

Table 1.

Weatherability of tallow derivative - petroleum wax mixtures on Granite Reef soil.

			Wax Rate (kg/m²)			
			0.25		0.50	
		Anti-	Pressure		Pressure	
Sample	Ratio	strip[1/]	5 psi	15 psi	5 psi	15 psi
Paraffin	—	N	30±10[2/];	—	39±8;	—
only	—	Y	123±38;		205±0;	60±40
140 wax	—	N	63±13;	—	109±2;	—
only	—	Y	159±36;	—	205±0;	83±13
AF706-69-I	—	N	50±16;	—	205±0;	68±28
only	—	Y	59±7;	—	205±0;	88±8
69-I/Par	1:1	N	175±30;	80	205±0;	143±23
	"	Y	205±0;	70±0	205±0;	118±2
69-I/140	1:1	N	175±30;	145	205±0;	133±53
	"	Y	178±18;	---	205±0;	178±28
AF729-82	—	N	0±0;	—	0±0;	--
only	—	Y	119±86;	15	50±15;	--
729-82/par	1:1	N	205±0;	95±5	205±0;	105±5
	"	Y	205±0;	110±15	205±0;	88±8
729-82/140	1:1	N	205±0;	76±15	205±0;	105±0
	"	Y	193±8;	—	120±85;	100
AF729-84	—	N	205±0;	88±18	0±0;	—
only	—	Y	143±13;	—	105±40;	--
729-84/Par	1:1	N	205±0;	138±33	205±0;	130±30
	"	Y	205±0;	83±13	205±0;	128±2
729-84/140	1:1	N	205±0;	90±0	205±0;	125±20
	"	Y	200±5;	40	205±0;	198±33
AF706-74-II	—	N	0±0;	—	0±0;	—
only	—	Y	108±98;	15	103±103;	125
74-II/par	1:1	N	205±0;	55±35	205±0;	95±15
	"	Y	205±0;	88±8	205±0;	253±13
	3:7	N	195±10;	75	205±0;	180±85
	"	Y	158±48;	15	205±0;	255±5
	2:8	N	205±0;	55±15	205±0;	130±10
	"	Y	205±0;	73±8	205±0;	110±30
	1:9	N	190±15;	55	205±0;	60±45
	"	Y	205±0;	38±33	205±0;	173±58
74-II/140	1:1	N	130±75;	35	185±20;	130
	"	Y	205±0;	180±85	205±0;	65±5
	3:7	N	205±0;	38±7	205±0;	135±40
	"	Y	185±20;	60	205±0;	178±83
	2:8	N	205±0;	30±20	205±0;	128±43
	"	Y	205±0;	38±13	205±0;	95±20
	1:9	N	205±0;	60±10	205±0;	60±20
	"	Y	180±25;	95	205±0;	180±85

1/ N = no antistrip; Y = 2% Emery 6639 in wax mixtures.

2/ Duplicate samples were run for a maximum of 205 minutes at 5 psi; then surviving samples were run at 15 psi until destroyed.

Table 2. Christmas tree harvest of the original and stump cultured Arizona cypress on the sand site and Eldarica pine on the clay site.

	Sell	Died	Culls
		%	
Cypress - Sand			
Original (Yr 3)	89	3	8
Stump Culture (Yr 5)	0	34	63
Total	89	37	71
Sellable trees/spot/yr (3 yr cycle) = 0.30			
Pine - Clay			
A) Original (Yrs 3 & 4)	88	4	-
" (Yrs 5 & 6)	8	0	0
Total	96	4	0
B) Stump Cultured (Yrs 5 & 6)	77	12	-
Total (A+B)	173	16	-
Sellable trees/spot/yr (4 yr cycle) = 0.22			
" " " " (6 " ") = 0.29			

Table 3. Height and growth of second planting of Eldarica pine on wax treated sand site.[1/]

	Rows I, II, III (Old Quetta)		Rows IV, V, VI (Old Cypress)	Row VII (New)
			cm	
1. Control	47		41	23
2. Deep-Till	45		37	34
3. 2 + Pine Duff	46		51	27
4. 2 + Silt Soil	45		40	21
5. QVAR - Salsola	43		38	29
AVE	45		41	27
Growth 1984	30		25	13
AVE Growth 1984		28		
AVE Growth 1979 planting		9		

1/ 2nd planting, drip irrigated, best of two trees/site.

TITLE: EFFECTS OF INCREASING ATMOSPHERIC CO_2 ON YIELD AND WATER USE OF CROPS

NRP: 20760 CRIS WORK UNIT: 5510-20760-006

INTRODUCTION:

This was the second year of a project whose main objective is to determine the long term effects of continuous CO_2 enrichment on the yield, water use, and photosynthesis of a variety of plants under optimal and limiting levels of water and fertility. The purpose is to document the possible future effects on crop production of a doubling of global atmospheric CO_2 concentrations. Secondary objectives are to determine the effects on physiological determinants of crop productivity, on water stress and stomatal behavior, and on biochemical reactions that limit photosynthesis. Staff members from the U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory are cooperating on the project.

In 1983, an experiment was conducted on field-grown cotton (Gossypium hirsutum L.), using open-top CO_2-enrichment chambers. The CO_2 treatments were ambient, 500, and 650 $\mu\ell\ \ell^{-1}$ in the chambers, as well as open-field control plots. All the cotton was well-watered, and there were two replicates of each treatment. The 1984 experiment again had the same CO_2 treatments with two replicates. The major change was to double the size of the experiment to include another irrigation level, so that in 1984 there were both well-watered ("wet") and water-stressed ("dry") treatments, as illustrated in the plot plan of Figure 1.

MATERIALS AND METHODS:

A. Culture of Experimental Crop:

The cotton crop was grown on the field just west of the Western Cotton Research Laboratory, Phoenix, Arizona. A plot plan is shown in Figure 1. The soil is Avondale clay loam (Fine-loamy, mixed (calcareous), hyperthermic, Anthropic Torrifluvent). Alfalfa had previously been grown on the field for about the last three years. The field was ploughed and furrowed on 16 March 1984 and a preplant herbicide, Karmex, was applied on 23 March. It was pre-irrigated with 230 mm of water on 27 March. Urea fertilizer was applied at a rate of 75 kg/ha on 5 April, and then the field was tilled with a lister hoe. The field was planted to Deltapine-61 cotton on 16 April 1984. A variety change was made from 1983 when Deltapine-70 was grown because in 1983 the cotton was planted late in June and Deltapine-70 is a shorter season variety than Deltapine-61. The cotton was planted in north-south rows at a 40-in (1 m) row spacing, on ridges with furrows in between, as commonly used for flood-irrigated cotton in Arizona. Following normal

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[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product listed by either the authors or the U. S. Department of Agriculture.

practices, the tops of the ridges were knocked off on 20 April, which was about 2 days after germination but prior to emergence. The practice removes the soil surface crust, thus facilitating emergence. The stand was thinned to 100,000 plants/ha, and a few gaps in the stand were filled using transplants.

Immediately after planting, two neutron access tubes were installed in each plot, one in the exact center in the middle row and the second about 30 cm west and 50 cm south of the first. During the course of access tube installation, a gravel layer was discovered in the field at a depth greater than 1.6 m at the south end of the field but gradually at shallower depths to about 1 m at the north edge. Consequently, the neutron access tubes at the south end (IW plots in Figure 1) were all installed to a depth of 1.6 m whereas those at the north (IIW plots in Figure 1) were installed to about 1 m with intermediate installation depths in between.

After the neutron access tubes were installed, erection of the open-top chambers began. The chambers were identical to those described in the 1983 Annual Report. The CO_2 treatments were initiated on 2 May 1984. The CO_2 sampling, enrichment, and control system was the same as used in 1983, except twice as many field sites were involved.

Psychrometers were installed at about the 1.5 m height in the south-west corner of each chamber or field plot. A Gill (R. M. Young and Co. Model 35001[1]) propellor wind vane was installed at the 2.5 m height on a mast in the center of the field. A Spectran Model 4048 pyranometer was installed on an arm of the same mast at a height of 2 m. Hourly average dry and wet bulb air temperatures, wind speed, and solar radiation were recorded each hour on an automatic data acquisition system.

As illustrated in Figure 1, the field was divided into four basins with four plots per basin. Thus, these four sets of plots (Rep I - wet, Rep I - dry, Rep II - dry, Rep II - wet) were each irrigated as a unit.

The wet plots were flood irrigated on a 2 week schedule, as is common practice for the area (Table 1). The dry plots, on the other hand, were irrigated on a three week schedule, thus subjecting their plants to more water-stress. Unfortunately, unusually heavy rains (Table 1) upset the irrigation schedules, so the dry treatment was not stressed as often or as severely as planned. The total amount of irrigation plus rain applied to all the plots was greater than planned.

As will be described in succeeding sections, numerous measurements of plant height, leaf area, biomass accumulation, flower and boll number, leaf photosynthesis, leaf diffusion resistance, leaf temperature, soil moisture content and water use, leaf water potential, soil CO_2 fluxes and concentrations, and insect populations were made during the course of the season. The middle row (3 m) was used for the final harvest on 17 October.

One evening per week from 11 June until 6 August Vapona in shallow dishes with a napkin wick was placed in the blower cabinettes for insect control. This procedure distributed the insecticide throughout the

chamber plant canopies, but the outside plants did not receive the treatment. Other insecticide treatments included spraying chambers IID2 and IID1 with Kelthane for red spiders on 18 June. Temik was applied to all chambers on 20 June. Sevin at 2 kg/ha and Kelthane at 1 kg/ha were sprayed on the cotton on 24 July. Some visible damage occurred to some of its upper leaves. In addition to the preplant application of urea at the rate of 75 kg/ha on 5 April, an additional sidedress of urea was applied in June at 75 kg/ha. The residual nitrogen from the previous alfalfa crop plus the applied fertilizer apparently supplied adequate nutrient. Concentrations of leaf petiole nitrogen (4th leaf) were measured periodically through the season (Table 2). They decreased markedly with time through the year, but no more than normal for a cotton crop.

B. CO_2 Concentrations:

CO_2 concentrations were continually recorded, as described in detail in the 1983 Report. About 30 seconds were required for the infrared CO_2 analyzer to stabilize on a new reading after switching from one plot to another. A single CO_2 observation was taken of CO_2 concentration for an ambient plot, but for the enriched plots, 30 observations were taken over a one minute period before switching to the next plot. Each hour, zero and span gas were also routed through the analyzer for automatic calibration, which required another minute. After each integer hour on the clock, the scan of all the plots was completed, and then hourly average CO_2 concentrations were computed and recorded. Because there were 16 plots, and about 20 minutes were required per scan of all the plots, these hourly averages usually included 3 observations from the ambient plots and 90 observations from the enriched plots.

A computer program was written to summarize the CO_2 observations over the entire season for each plot. After sunrise, the system normally increased the CO_2 flow rates to compensate for the greater atmospheric turbulence and greater exchange of air in the open top chambers during daytime, and vice versa after sundown. To see any diurnal patterns of CO_2 concentrations, therefore, the CO_2 observations were sorted and averaged by hour of the day. The results are presented in Figures 2, 3, 4, and 5 for the IW, ID, IID, and IIW plots, respectively. The program was also run on the 1983 data for completeness, and these results are presented in Figures 6 and 7 for Reps I and II, respectively.

Perusing Figures 2 - 7, it is apparent that the ambient concentrations undergo a diurnal variation from about 350 $\mu\ell\ \ell^{-1}$ in daytime to 400 $\mu\ell\ \ell^{-1}$ at night. The enriched plots also have some diurnal variation but less pronounced because of the controlled set points at 500 and 650 $\mu\ell\ \ell^{-1}$. After sunrise each day, the concentrations decreased below set points for an hour or two until the system responded to the higher level of atmospheric turbulence. After sunset, concentrations rose above the set points until they similarly responded to calmer night conditions.

Also plotted in Figures 2-7 are the standard deviations of the individual CO_2 concentration observations. The bands reveal considerable fluc-

tuation, even in the ambient concentration. However, overall, the CO_2 control of the enriched chambers was quite good, and the standard deviation bands overlap only occasionally.

The overall CO_2 concentration means and standard deviations are tabulated in Table 3. In 1984, they averaged 350 ± 55, 355 ± 60, 511 ± 81, and 662 ± 114 $\mu\ell\ \ell^{-1}$ for the open field plots, ambient, "500", and "650" chambers, respectively. In 1983, they were 368 ± 56, 356 ± 47, 523 ± 90, and 643 ± 101 (Table 4).

RESULTS:

A. Leaf Area, Biomass, and Yield:

Destructive harvests of plants in the two outside rows of the chambers were taken nine different times during the season. Each time, 3 plants were taken in a rotating pattern of consecutive quadrants of the two rows so as to distribute the resultant canopy gaps as evenly as possible and minimize the overall impact on the remaining plants. No intermediate destructive harvesting was done on the middle row, and all of the plants in it were used for the final harvest at the end of the season.

Following each intermediate harvest, leaf area was measured by passing the leaf blades through a LI-COR leaf area meter. Counts were made of the number of nodes, open bolls, and green bolls. Dry weights of leaves and stems, open bolls, green bolls, and roots were measured after drying separately in an oven at 70°C.

The accumulation of leaf area index during the season is presented in Figure 8. By day 234, the plants grown at 650 $\mu\ell\ \ell^{-1}$ had 74% greater leaf area than those at ambient for the wet treatment. The 650 plants from the dry plots had 18% more leaf area than the dry ambient plants on day 234, although for most of the season the 650 plants had relatively more area than on day 234.

The accumulation of dry weight of bolls is shown in Figure 9. Obviously, the 650 $\mu\ell\ \ell^{-1}$ CO_2 concentration greatly stimulated boll growth. The weights of bolls from the "650" chamber were nearly double those from ambient "350" chambers for both wet and dry treatments. By season's end, the irrigation treatments had little effect, there being almost no difference in boll weight between wet and dry at 350 and only a small difference at 650 $\mu\ell\ \ell^{-1}$ CO_2. However, earlier in the season, between days 200 and 240, some rather large boll weight differences existed between the wet and dry treatments. Apparently, however, rains superimposed on the irrigation supplied enough water for the dry plants to nearly completely recover their yield potential.

The number of bolls is shown in Figure 10, and the pattern is the same as for weight. There were nearly twice as many flowers at 650 compared to 350 $\mu\ell\ \ell^{-1}$ CO_2. At season's end, irrigation treatment had little effect, although earlier between days 200 and 240, the wet plots had

considerably more bolls. There was a marked recovery in boll number following the day 221 irrigation, and the extra rain during the latter part of the season facilitated complete recovery from water stress.

A comprehensive tabulation of the final destructive harvest results are presented in Table 5. The CO_2 enriched plots were about 7% taller for a doubling (650) of CO_2 in the wet plots and 26% taller in the dry plots. The number of bolls was greatly increased by CO_2 enrichment as will be discussed in more detail shortly. Total dry matter production was increased by 50 and 95% in the wet plots by the 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2 treatments, respectively. In the dry plots, the increases were 19 and 71% respectively. The seed cotton yield increases closely paralleled the dry matter increases. Seed cotton was increased by 44 and 94% in the wet plots in the 500 and 650 CO_2 treatments, respectively, and by 32 and 77% in the dry treatments.

As already revealed by Figures 8-10, the plants in the dry plots recovered from the water-stresses to which they were subjected, and at ambient CO_2, the drys slightly outyielded the wets. At the higher CO_2 levels, however, the plants in the wet plots responded somewhat more to the CO_2 resulting in the 94% increase in yield due to the 650 $\mu\ell\ \ell^{-1}$ CO_2 treatment compared to the 77% increase in the dry plots. This result is in conflict with other data reported in the literature that indicate that plants respond relatively more to CO_2 when subjected to water stress. However, our "dry" plants obviously were not water-stressed for their entire lifetime, so the comparison with the other studies may not be valid.

Referring again to Table 5, it is apparent that the percentage of lint in each boll was not affected by either the CO_2 or the irrigation treatments. Neither was the size of the seeds affected in any consistent way. There was no effect of CO_2 on fiber length in the wet plots, but the dry, CO_2-enriched plots had 6% shorter fiber than the dry ambient plots. There were some interesting differences in fiber fineness. Fineness increased by 10 and 15% in the wet plots at CO_2 concentrations of 500 and 650, respectively, and in the dry plots by 4% at both CO_2 concentrations. The fineness data indicate an improvement in lint quality with increasing CO_2 whereas the fiber length data show a decrease in quality in the dry plots with increasing CO_2.

CO_2 enrichment also did not affect harvest index in either the wet or dry plots (Table 5). However, the harvest index of the dry plots was consistently higher than that of the wet plots at all CO_2 levels.

The all-important yields of seed cotton (lint + seeds) are isolated in Table 6. As discussed previously, at 650 $\mu\ell\ \ell^{-1}$ CO_2 there was an astonishing 94% greater yield than at ambient for the wet plots with the "500" treatment yields about midway between. The yield response to CO_2 was similar in the dry plots with the 650's outyielding the ambients by 77%.

Numbers of flowers, percentage of flowers that resulted in harvestable bolls, and weight of lint per boll are all components of yield and these

data are presented in Table 7. The flower and boll retention data will be discussed in detail in the next section. The amount of lint per boll did not vary much with treatment, nor did the percentage of blossoms retained. There were increases of about 75% in the number of flowers going from ambient to 650 $\mu\ell\ \ell^{-1}$ CO_2 for both wet and dry treatments, so this increase in flower number was the major component of the increase in yield with increasing CO_2 concentration.

B. Flowering and Boll Retention:

On every normal working day during the whole season, each flower in the middle row of cotton in each chamber or plot was counted and then marked with a small tag bearing the day of the year that the flower appeared. At the end of the season, the tags were collected from the bolls that were retained on the plants, sorted by week, and counted. These counts from the middle row were in addition to those made on the destructive plant samples from the outside rows, as discussed in the previous section.

Irrigation had no consistent effect on flowering or boll retention. Therefore, irrigation is combined with replications in the tables.

A rather strong chamber effect was evident. Open plots flowered more early in the season than any of the chamber plots (Table 8). This probably resulted from a difference in insect damage; fewer squares abscised in open plots than in chambers early in the season. A difference in insect damage may have continued through the season because plants in the open plots also retained a higher percentage of bolls throughout the season than any of the chamber plots (Table 9). Therefore, as many bolls were set in the open plots as in the ambient chambers (Table 10) despite fewer flowers being produced in the open plots in the later part of the season (Table 8).

Elevated CO_2 increased the number of flowers produced (Table 8), but had no consistent effect on percentage boll retention (Table 9). The total number of bolls set by day 237 (24 August) increased in proportion to the elevation in CO_2 content of the air. Boll production increased 41% with 500 $\mu\ell\ \ell^{-1}$ CO_2 and 82% with 650 $\mu\ell\ \ell^{-1}$ CO_2 (Table 10). These results are consistent with those of earlier experiments; cotton fruiting increased markedly when CO_2 content of the air was increased.

C. Photosynthesis:

Net photosynthesis of cotton in the CO_2 enrichment experiment was measured between 1245h and 1500h on 20 days between 17 July and 29 August 1984. We used a technique based on CO_2 depletion by leaves enclosed for a brief time in a handheld chamber. The chamber was constructed from a pair of transparent plexiglass domes that were hinged at one point to facilitate rapid inclusion of single cotton leaves in a horizontal plane within the chamber. Closure of the chamber was effected by a pistol grip mechanism, making it a single-handed operation. The spherical shape minimized the chamber volume (1.74 liters) to cross sectional area, and maximized the light transmittance characteristics while keeping internal reflectances within the chamber to a

minimum - design characteristics not presently available on commercial photosynthesis chambers. When the chamber was closed on a leaf, a battery operated solenoid triggered the extraction of a 10 ml reference air sample from the chamber. Then after a 13.5 second time interval a second sample was automatically withdrawn from the chamber. A small fan enclosed within the chamber circulated air continuously. Temperature buildup within the chamber during this short period was minimal. With this chamber and the dual syringe sampling technique it was possible to sample leaves at approximately 1.5 to 2.0 minute intervals.

Plastic syringes containing air samples from the chamber were stored in an ice chest cooled by several packages of "blue ice". Control syringes containing a 10 ml sample of primary standard CO_2 were kept in the ice chest to provide a check on contamination of samples during the measurement period. Within 30 to 45 minutes of their collection, CO_2 concentrations of samples and controls were determined in the laboratory, using an infrared gas analyser (IRGA: Analytical Development Company, Type 225 MK3) that was interfaced with an HP printing integrator. The system was calibrated at 2 to 3 intervals during each day's measurement sequence using a primary standard CO_2 source (376 or 388 or 499 $\mu\ell\ \ell^{-1}$, depending on availability). The measured difference in CO_2 concentration between the initial reference sample and the sample acquired 13.5 seconds later was converted to a net photosynthetic rate (Pn in μmol $CO_2 m^{-2} s^{-1}$) by the following relationship

$$Pn = \frac{(209.30)\left[\dfrac{\Delta CO_2(\mu\ell\ \ell^{-1} \text{ X Ambient pressure (mb)}}{\text{chambertime (sec) X Ambient temperature (°K)}}\right]}{\text{leaf area (cm}^2)}$$

where 209.30 is a constant which incorporates the molecular weight of CO_2, chamber volume, standard temperature and pressure relations and time and unit area conversions, and ΔCO_2 ($\mu\ell\ \ell^{-1}$) is the difference in CO_2 concentration between first and second syringe samples.

Leaves for the photosynthesis measurements were chosen from the center of the three rows of cotton within each chamber to minimize any effect that shading by the walls of the chamber might have on photosynthesis. At the start of each week, one or two fully expanded leaves at approximately the 4th node from the main stem terminal were tagged and measured with a centimeter scale in each CO_2 treatment and irrigation level combination. Pn measurements were then conducted on these same leaves for up to a 5-7 day interval. Constraints on destructive plant sampling within the small chambers required a non-destructive means of estimating leaf area. This was accomplished by sampling a series of leaves from the field in early August and subjecting easily obtained linear leaf measurements to multiple regression techniques with leaf area as the dependent variable. Results yielded the relation

$$Y = -58.4 + 7.11A + 4.89B + 3.40C$$

$$r^2 = 0.88 \quad SE = 5.7 \text{ cm}^2$$

where A = distance from the petiole to the tip of the main center lobe of the leaf,

B = overall width of the leaf at a point 1/3 the distance from the petiole to the tip,

C = distance from the petiole to the tip of a lateral lobe of the leaf, and

Y = the flattened leaf area of an entire leaf (cm^2).

This equation produced an acceptable leaf area estimate which enabled a relative comparison of photosynthetic rates between treatments.

Measurement of Pn by any technique remains more an art than a science. Use of the handheld chamber for the measurements did not prove an exception to this generalization; our results showed a great deal of variability between and among treatments. Operator error in sampling technique and IRGA analysis was a major source of this variability. In the analysis which follows, 23 out of 512 Pn determinations (<5%) were deleted because the samples were obviously contaminated or mislabeled. Inability to precisely measure leaf areas, inappropriate and uneven insecticide applications, and untimely breaks in irrigation berms contributed further to the variability, but no attempt was made to compensate for them.

The midday Pn of sunlit cotton leaves is shown in Figures 11 and 12, for the wet and dry treatments respectively. Each data point represents the average value observed for all leaves measured in a particular CO_2 and water treatment combination. Replicate treatments have been combined in these figures. Pn was consistently higher in the ambient chamber than in the open field plot in both the wet and dry irrigation treatments. This may be due to micro-climatic differences within the chamber. Temperature and humidity were typically higher within the chambers during the time of measurements. Higher cotton leaf temperatures and rates of gaseous exchange in the chamber may have contributed further to this "chamber effect". In the wet treatment chambers, we observed consistent differences in Pn which could be attributed to CO_2 concentration. The differences were minimal just prior to an irrigation when the plants were stressed and at a maximum during the one to two week interval following an irrigation.

In the dry treatment, however, the effect of CO_2 on Pn was not as obvious (Figure 12). Plants growing in the CO_2 enriched chambers were larger and invariably wilted first as stress developed following an irrigation. In fact, plants grown at 500 and 650 $\mu\ell\ \ell^{-1}$ invariably showed symptoms of stress 7-10 days before plants in the ambient chamber and open field plots. This is reflected in Pn data of Figure 12 which shows very little difference between enriched and ambient chambers prior to the irrigation on day 221. In fact the 650 $\mu\ell\ \ell^{-1}$ cotton showed lower Pn than the 500 $\mu\ell\ \ell^{-1}$ cotton during much of this time. The 500 $\mu\ell\ \ell^{-1}$ cotton also exhibited a rapid response to the relief of stress by a 100 mm rainfall on day 210. Both enriched treatments showed an increase in Pn following irrigation.

Figures 11 and 12 show considerable natural variation caused by daily changes in solar irradiance, differences in leaf age and specific leaf

weight and differences in plant water status between CO_2 treatments within a given irrigation regime. Thus we felt the most effective way to analyze the data would be to compare each of the treatments with their respective controls. The effect of the chamber on Pn was examined by taking the ratio of average midday Pn of leaves within the ambient CO_2 chamber to the Pn of leaves outside the chamber (the "chamber effect"). From 17 July until 17 August 1984, this chamber effect ratio was 1.19 for the wet treatments and 1.15 for the dry treatments (Table 11). When similar ratios were formed between the 500 $\mu\ell\ \ell^{-1}$ CO_2 chambers and the ambient control chamber, we observed a 23% and 32% increase in Pn for the wet and dry irrigation treatments, respectively. In the 650 $\mu\ell\ \ell^{-1}$ chambers we observed a 51% increase in the wet treatment and a 39% increase in the dry treatment when compared with the ambient chamber controls.

The net photosynthesis data provide strong support that CO_2 enrichment enhances productivity of cotton. However, the increase in photosynthetic rate for a doubling of the CO_2 concentration is approximately half the observed increase in marketable yield. The large yield increase can be explained by the greater leaf areas in the enriched treatments and hence higher productivity per unit ground area than indicated on the basis of the data in Table 11 alone.

Several important questions remain to be answered. Among them is whether leaf respiration is altered by CO_2 enrichment or the resulting increase in leaf temperature which accompanies the partial closure of stomates at the higher CO_2 levels. A second important question pertains to the response of leaves to changes in CO_2 once they have been acclimated to an elevated CO_2 concentration. Limited observations suggest that short term deviations below the acclimated CO_2 level have the effect of reducing photosynthesis to a lower than expected rate.

D. Stomatal Resistance:

Stomatal resistance measurements began on 7 June 84 (Day of Year 159) and continued through 10 October (DOY 184). Three fully sunlit leaves were randomly selected for this purpose at the top of the canopy from the center row of each CO_2 and water level treatment. Stomatal resistance was determined with a LI-COR steady state porometer on both the adaxial and abaxial leaf surfaces. A leaf stomatal resistance for each treatment was then calculated by summing the parallel resistances of both surfaces and averaging the resistance for the three leaves. Measurements were made on 22 days throughout the growing season. Instrument failure and cloud cover affected the integrity of the data on 10 of these days, leaving 12 days of measurements dispersed randomly through the season on which an analysis of variance was performed. The analysis of variance assumed a randomized complete block design with days as the blocking criterion. Treatment means were compared using orthogonal contrasts.

The seasonal pattern of stomatal resistance is illustrated in Figure 13 for the wet treatment. No consistent effect of increased CO_2 con-

centration on stomatal resistance under well-watered conditions was noted until late in the season, and then only in the 650 μℓ ℓ^{-1} treatment. The seasonal stomatal resistance means together with their standard errors for the open, ambient chamber, 500 and 650 μℓ ℓ^{-1} treatments were 60.5 ± 8.9, 55.5 ± 8.1, 63.8 ± 11.7, and 78.3 ± 12.7 s m^{-1} respectively. The analysis of variance indicated that there was no statistically significant effect ($P \leq 0.01$) of increased CO_2 concentration on stomatal resistance in any of the wet treatments. Furthermore, the difference of 5.0 s m^{-1} between the open field and the ambient chamber was not significant, indicating the lack of a chamber effect on field-grown well-watered cotton.

The seasonal trace of stomatal resistance for the dry treatment is shown in Figure 14. The peaks at days 192 and 219 occurred just prior to irrigation. The water stress effect was more strongly observed in the 650 μℓℓ ℓ^{-1} treatment than in the 500 and 650 μℓ ℓ^{-1} treatments were 66.6 ± 11.0, 82.9 ± 9.1, 127.7 ± 37.0 and 136.6 ± 32.6 s m^{-1}, respectively. Comparison of treatment means indicated that the 500 and 650 μℓ ℓ^{-1} treatments were significantly different ($P \leq 0.01$) from the mean ambient chamber resistance. The 500 and 650 μℓ ℓ^{-1} CO_2 treatments were not, however, significantly different from each other. The difference of 16.3 s m^{-1} between the open and ambient chamber was also nonsignificant.

Comparison of identical CO_2 concentrations across water treatmentl indicated that stomatal resistances at 500 and 650 μℓ ℓ^{-1} CO_2 concentrations in the dry treatments were significantly higher ($P < 0.01$) than the resistances measured in the well-watered treatments at identical CO_2 concentrations. The average differences for the 500 and 650 μℓ ℓ^{-1} treatments were 63.9 and 58.3 s m^{-1}, respectively. Lack of irrigation water did not significantly increase the stomatal resistances measured in either the open field or the ambient chamber when compared to the well-watered plants. These results indicate that stomatal resistance of cotton plants is strongly influenced by CO_2 concentration in the presence of mild water stress. The results of this experiment also indicate that it is difficult to ascribe the increased water-use efficiency of plants exposed at high CO_2 levels to increased stomatal resistance. The large variability inherent in stomatal resistance measurements decreased the precision of the mean estimates which resulted in many non-significant statistical tests. It should be noted however, that stomatal resistance in both the wet and dry treatments increased with increasing CO_2 concentration. When coupled with the increases in leaf area (Figure 8), these data support the observation of small and inconsistent differences in water use per unit of land area, as will be discussed in a subsequent section.

E. Leaf Temperatures:

Leaf temperatures were measured using an infrared thermometer on many clear days during 1984. Similar data were obtained during 1983 and the data from both years have been analyzed. During 1983, the measurements were taken over the center of the middle row pointing down at an angle of 30° from vertical. Twenty observations were taken and averaged. In

1984, ten observations were taken from the east and west sides of the row at a slight tilt from vertical, and these were composited to form the desired foliage temperature.

Previous studies had shown the important influence of air vapor pressure deficit on leaf temperatures. Therefore, vapor pressure deficits were computed from the wet and dry bulb temperatures of the psychrometers installed in each chamber and field plot. These psychrometric data were recorded automatically as hourly averages by the data acquisition system.

Figures 15 and 16 show the leaf minus air temperatures versus vapor pressure deficit for 1983 and 1984, respectively. The upper left graphs show that the ambient chambers and the open field plots reacted similarly to vapor pressure deficit. The two data sets are indistinguishable even though in absolute temperature the leaves in the ambient chambers were somewhat warmer because the air was somewhat warmer in the chambers.

Scanning from the upper left (ambient) to upper right ("500") to lower left ("650"), the leaf temperatures were warmer with increasing CO_2 concentration for any given vapor pressure deficit.

The lines on the graphs in Figures 15 and 16 were fitted by regression but forced through a common point for all three CO_2 concentrations. The lines are reproduced together in the lower right graph of both figures. At low values of vapor pressure deficit (0.8 kPa), a doubling of CO_2 concentration produced less than a 1°C increase in leaf temperatures. In drier air with a vapor pressure deficit of 4.0 kPa, a CO_2 doubling caused an increase in leaf temperatures of about 2°C. Such an increase in leaf temperature must be ascribed to a slower transpiration rate per unit of leaf area at the higher CO_2 concentrations. However, a lower transpiration rate implies a higher stomatal resistance, in conflict with the stomatal resistance measurements for the well-watered cotton (Figure 13). There are many more temperature measurements, and so the temperature data are likely to be more reliable, indicating that the increased stomatal resistance of CO_2-enriched, well-watered cotton, though not significant statistically, was biologically significant.

F. Leaf Water Potential:

Several times during the season, leaf samples were taken for pressure-volume analysis - that is leaf water potential as a function of relative leaf water content. The samples were taken just before dawn or near mid-afternoon. Eight leaves could be handled as a batch, so one leaf was taken from each plot or chamber in one rep only each sampling time. A plastic Zip-lock bag was humidified with a breath of air just before the youngest fully expanded leaf from a plant was severed with a razor blade and then sealed in the bag. The bags were stored under a wet towel in a styrofoam chest for transport to the laboratory.

Once inside the laboratory, the leaves were weighed, and then their petioles were placed in beakers of water to hydrate them. A plastic

tent and an opaque cover were placed over them to produce a saturated atmosphere. The leaves were allowed to hydrate for at least six hours.

After hydration was stopped, the leaves were weighed to obtain the saturated weight. Then they were replaced in their Zip-lock bags. One by one they were then placed in a Scholander bomb (Soil Moisture Equipment Corp., Model 3000). They were wrapped with the plastic bag with their petiole protruding. The pressure in the bomb was increased with compressed N_2 at a rate of 0.03 - 0.07 MPa/s until sap began to exude from the petiole. The pressure was noted, and then the process was repeated with another leaf. Between weighings and pressure bomb readings, the leaves were allowed to lose water by transpiration. About eight pressure-weight points were obtained on each leaf, at least enough to ensure that graphs of reciprocal pressure potential versus weight loss had become linear so that the potential at zero turgor could be determined.

After the pressure-bomb weighing runs were completed, the petioles were severed from the leaf blades and the the fresh weight of the petiole was measured. Then the leaf blades and petioles were dried in an oven at 70°C and weighed. Relative leaf water contents - (RLWC, %) were then computed from

$$RLWC = \frac{\text{fresh blade weight - dry blade weight}}{\text{saturated blade weight - dry blade weight}} \quad X\ 100$$

In the determination of RLWC's, the assumption was made that all of the water lost during the pressure bomb run was lost from the leaf blade and none from the petiole. Considering that the preponderance of stomates are on the blade and that the petioles are mainly conductive tissue, this assumption seems safe and reliable.

The leaf water potential data are still being reduced. For this report, a sampling of the results will be presented in Figures 17-20, which show the pressure-volume curves for leaves sampled on the afternoon 29 August and predawn on 30 August. The wet and dry plots had not been irrigated for 1 and 3 weeks, respectively. There are considerable scatter in the data. Figure 17 for the Rep I - wet plots sampled in the afternoon shows little difference between the CO_2 enriched plots or the open field. The ambient chamber data, on the other hand, are all to left of the other curves indicating less water in the tissue for any given water potential. Comparing Figure 18 to Figure 17, the curves for the leaves from the dry plots harvested that same afternoon (Figure 18) are all displaced downward to lower potentials, but there are essentially no differences due to CO_2 among the chamber treatments. The next morning, there were no differences among the wet plots due to CO_2 or between the open field and the chambers (Figure 19). The curves for the predawn leaves from the dry plots show a rather wide difference (Figure 20), with the CO_2 enrichment curves below the ambient curves. At 100% relative leaf water content, the water potential of the CO_2 enriched plots is lower than the ambient plots, as it is for all values of RLWC. On

the other hand, for any given level of water potential, the CO_2 enriched leaves did contain more water in their tissues. Considerably more analyses of the water potential - RLWC data for the many other sampling days remains to be done, but the general impression of the data is that there are few differences due to CO_2 among the wet plots, but that the curves from the CO_2 enriched dry plots fall below those from ambient dry plots indicating more water in the tissue of the CO_2 enriched leaves for any given water potential level.

By 29 August, the destructive whole plant harvests for leaf area and biomass accumulation from the outside rows had been completed, so some additional leaf material could be sacrificed for water potential measurements. On the afternoon of 29 August 1984, 6 leaves were sampled from each chamber or plot as described previously. However, instead of hydrating them, they were placed in the pressure bomb for an immediate determination of their total water potential at the field condition. These results are presented in Figure 21 where water potential is plotted against CO_2 concentration. It is obvious that CO_2 concentration had no effect on leaf water potential in the wet plots. The leaves from the dry plots were all at much lower potentials, as expected, but the effect of CO_2 was not consistent. The CO_2 enriched plants in Rep II - dry were at a lower potential than the ambient controls, whereas in Rep I - dry there was no difference between the ambient and the 650 $\mu\ell\ \ell^{-1}$ CO_2 treatment, but the 500 treatment leaves were at a lower potential.

It is difficult to draw definitive conclusions from these few data about the interaction between CO_2 concentrations and water potential. It appears that the larger CO_2 plants use as much water per unit of land area as the unenriched plants (see next section), and that differences in total water potential due to CO_2 enrichment are rather small in the field. However, there are indications that at any given potential, CO_2 enriched plants subjected to water stress contain more water in their tissue (Figures 18 and 20).

G. Water Use:

The amount of water used by the crop for evapotranspiration was determined by soil moisture depletion measurements. The soil water content was measured twice weekly (usually) with neutron modulation apparatus. As mentioned earlier, the gravel layer at depths of more than 1.6 meters at the south end of the field to about 1 meter at the north end prevented the access tubes from being installed to the desired 1.6 m everywhere. To make comparisons between plots, therefore, the moisture depletion from the top 0.8 m was computed, and the lower depths were ignored in the data to be presented. Actually the computations were also done to the deepest depth possible in each basin (Figure 1) and the relative water use among CO_2 treatments within each basin had the same pattern as the 0 to 0.8 m computations.

The unusually large number of rains presented problems also. Sometimes there was only one soil moisture observation between rains, making a water use determination for these periods impossible. In such cases the

rate of water loss was assumed to be the same as that of the time period immediately following in Figures 22-25. Water content data plots are shown for each day of the year for the Rep I - wet, Rep II - wet, Rep I - dry and Rep II - dry plots respectively. The bottom of the figures also shows the amount of irrigation and rainfall, the rainfall being the lines showing less than 150 mm of water. For days of irrigation and large rainfall, the moisture contents at the beginning of the day were extrapolated from measurements for previous days, and the moisture contents at the end of the day were extrapolated backward from measurements made on following days. The rains near day 210 and 250 made these calculations difficult.

The cumulative water use from the top 800 mm of soil was calculated from the water content data in Figures 22-25. These cumulatives are presented in Figures 26-29. In Figure 26 for the Rep I - wet plots, it is apparent that from about day 190 to the end of the season, the water use increased with increasing CO_2 concentration. However, the pattern was not repeated in the Rep II - wet plots (Figure 27), which shows inconsistent CO_2 effects. The Rep I - dry plots that were CO_2 enriched used more water than the ambient (Figure 28). However, in the Rep II - dry plots, the 650 $\mu\ell\ \ell^{-1}$ chamber apparently used much less water, particularly after day 220 (Figure 27). Thus, there was an inconsistent effect of the CO_2 treatments on water use.

Figure 30 shows the total water use (from the top 800 mm of soil) for all of the chambers plotted against CO_2 concentration. This plot vividly shows the inconsistent effect of CO_2 concentration on water use. For two of the plots (Rep I - wet and Rep I - dry) water use went up with increasing CO_2 concentration, whereas for the Rep II - wet plots the differences were small, and then for the Rep II - dry plots the pattern was very erratic with the 650 $\mu\ell\ \ell^{-1}$ chamber showing very little water use. The more erratic Rep II data are from the rep that has the shallowest depth to the gravel layer (and the shortest neutron access tubes).

Many previous short-term studies with many plant species have shown a decrease in transpiration rate of an average of about 34% when CO_2 concentration was doubled, indicating that leaf stomatal resistance increased by about 34%. Our stomatal resistance measurements, on the other hand, show relatively little change of stomatal resistance of cotton with changes in CO_2 (Figures 13-14). In 1983, our lysimeter data indicated that a doubling of CO_2 concentration could reduce water use 5-10%, while neutron data showed no effect of CO_2 on water use. The 1984 neutron data in Figures 22-30 indicates that water use can actually increase with increasing atmospheric CO_2 concentration or produce small or inconsistent effects.

One effect of CO_2 on cotton is increasing leaf area (Figure 8). If leaf area increases proportionally more than transpiration per unit of leaf area decreases, the water use per unit of land area can increase. Thus, our data over the two years indicate that a doubling of CO_2 concentration is likely to cause slight negative or positive changes in water use

per unit of land area. Nevertheless, the accompanying huge increase in plant yield with increasing CO_2 concentration (Table 6) represents a huge increase in water use efficiency.

H. Evolution of CO_2 from the Soil:

In 1983, soil carbon dioxide fluxes were higher in the open field plots than inside the open-top chambers used in the carbon dioxide enrichment studies (Effects of Increasing Atmospheric CO_2 on Yield and Water Use of Crops, Annual Report 1983). Flux measurements were repeated in the 1984 cotton experiment in all the chamber plots at two moisture levels for a total of 16 plots. The flux results continued to exhibit similar results as the 1983 study. To find the cause for such behavior, the soil atmosphere was sampled to determine carbon dioxide concentrations at the various depths of the profile both inside and outside the chambers.

Stainless steel sampling tubes were fabricated by welding 2.4 mm tubing to hypodermic needles. These were inserted into the soil at various depths of 5-, 10-, 20-, 40- and 60-cm in several sites inside and outside the growth chambers. Two ml of soil air were taken with a hypodermic syringe, and the samples were analyzed for carbon dioxide concentration with an infrared analyzer (Carbon Dioxide Analysis with a Modified Infrared Gas Absorption Technique, Annual Report for 1980).

Two soil carbon dioxide concentration and distribution patterns were obtained, as illustrated in Figure 31. The carbon dioxide concentrations were much lower in the samples taken from inside the open-top chambers than those outside. The soil CO_2 concentration results explain why the fluxes outside the chambers were different than those inside. The lower concentration gradients inside the chambers lead to a lower flux value. When the blower systems used to enrich the chambers with CO_2 and maintain temperature were turned off at the end of the season, the soil CO_2 concentrations in the chambers started to increase gradually and reached those of the open field plots. The equilibrium time was about four weeks.

Flux measurements taken at the same time also were different just before the blowers were turned off, and then gradually became the same with time.

Apparently a different type of soil atmospheric condition can be created within the chamber with the forced flow of air needed to maintain constant carbon dioxide and temperature levels. Soil carbon dioxide flux can be determined with a static or dynamic method. We used the static method so that any external variable should have been the same inside and outside the chamber. Air turbulence caused by the blower can cause greater interchange of soil gases resulting in the lower level of carbon dioxide in the soil profile than normal. Soil drying could also cause lower water levels in such instance and would affect microbial activity, which is the source of most of the carbon dioxide in the soil.

I. Insect Populations:

Insects were collected on sticky traps (Sticky Strips, Olson Products, Medina, OH 44358; 15 by 15-cm yellow cardboard sticky-coated on both surfaces) which were impaled on plant stakes, placed at the top of the cotton plant canopy. Traps were exposed for a 3-day period each week, starting on 3 August and continuing to 12 October. After exposure they were wrapped in clear plastic, and taken to the laboratory where the different insect groups were counted under the microscope. Thrips were collected over a longer period of time, from traps set out at biweekly intervals from 15 June to 5 October. During part of this time, at weekly intervals from 11 June to 6 August, a large petri dish with 10 ml 2.2 dichlorovinyl dimethyl phosphate (Vapona*) and a napkin wick was placed in each blower cabinet supplying air and CO_2 to the enclosed plots, as a general insect control measure.

Comparisons of the total number of insects collected in the dry and wet plots of each of the open, ambient, and two CO_2 treatments during each of the 11 weeks, or 10 in the case of the thrips, were made by a paired t-test. Differences were considered significant at the P=0.01 level. The results of the counts of the six insect populations are presented in Table 12.

Flea beetle - The desert corn flea beetle, Chaetocnema ectypa Horn, was the species collected. Late in the summer it is not injurious to cotton, although large populations in seedling cotton might cause concern. In our samples, the total number of beetles collected during a single sampling period increased from 111 on 10 August to 256 on 24 August, then gradually declined to 11 beetles on 12 October. Populations were similar in the open and in the ambient chambers (Table 12), but were significantly reduced in the 500 carbon dioxide treatment and still further reduced in the 650 carbon dioxide treatment.

Pink bollworm - The pink bollworm, Pectinophora gossypiella (Saunders), collected on the traps, increased in numbers from a total of 6 on 3 August to 206 on 7 September and then remained at from 165 to 178 for the next few weeks. Some of the moths had red dye in their bodies indicating that they had escaped from a near-by rearing facility. The open chambers had significantly more moths, so the chambers apparently tended to reduce the number of moths. The high carbon dioxide level treatment had significantly fewer moths than ambient and 500 carbon dioxide treatments.

Leafhoppers - Several species of green and brown leafhoppers were collected. The total leafhopper population increased to a peak of 418 leafhoppers at the end of August, dropped to 99 in mid-September, and increased rapidly to a peak of 650 in early October. The enclosures reduced the numbers in the ambient treatment by almost one-half and the number of individuals in both of the carbon dioxide treatments was significantly reduced from the ambient treatment.

Predaceous fly - This fly, Draepetis divergens Loew (Empiidae) (det. by E. J. Rogers) has not been associated with any particular host but,

during 1984, adults were observed with sweetpotato whiteflies in their beaks in both laboratory and field (G. D. Butler, unpubl. data). Populations of the fly generally increased from early August to October, with a total of 875 collected on 5 October. Only 14% as many adults were collected in the ambient treatment as the open treatment. Populations were further reduced in both the carbon dioxide treatments, with only 6% and 3% as many flies in the 500 and 650 carbon dioxide treatments, respectively, as the open treatment.

Sweetpotato whitefly, Bemisia tabaci (Gennadius) - Populations increased from early August to mid October at an exponential rate similar to that observed in commercial cotton fields in Arizona and California in previous years. There was no difference in the rate of whitefly buildup in any of the treatments. The number of insects in the two carbon dioxide treatments was similar to that observed in the ambient treatment.

Thrips - The most abundant insect collected was thrips. The peak population was observed on 10 August. There were no significant differences in the total populations of any of the treatments even though the three chamber treatments received insecticide treatments during part of the sampling period.

These data indicate that the populations of some insects are unaffected by CO_2 concentration, whereas others decreased with increasing CO_2 concentration. None of the counted species were increased in population at the higher CO_2 concentration. The reason that some populations decreased at higher CO_2 concentrations is unknown. It is also unknown whether their populations would be depressed at high CO_2 if the CO_2 concentration had been high everywhere in the field, as it will be in the future. Nevertheless, these data indicate that insect problems are not likely to get worse and may even get better in a future higher-CO_2 world.

SUMMARY AND CONCLUSIONS:

The field CO_2-enrichment experiment on cotton was continued during the 1984 growing season from April through October. The open-top chamber technique was used to provide CO_2 levels of ambient, 500, and 650 $\mu\ell\ \ell^{-1}$ over 3 X 3 m plots. Open field plots were also included. There were two irrigation schedules - "wet" irrigated at normal 2 week intervals, and "dry" irrigated at 3 week intervals. All treatments were replicated twice. An automatic CO_2 enrichment/sampling system was used to control the CO_2 concentrations. The actual achieved season-long means and standard deviations of the individual observations were 350 ±55, 355 ± 60, 511 ± 81, and 662 ± 114 $\mu\ell\ \ell^{-1}$ CO_2 for the open fields, ambient chambers, "500" chambers, and "650" chambers, respectively.

The cotton was highly responsive to the CO_2 treatments. In the wet plots the seed cotton (lint and seed) yields were increased 46 and 92% by the 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2 treatments, respectively. In the dry plots the yield increases were 32 and 77%, respectively. Leaf area and dry matter production increased similarly. The primary component

contributing to its yield increase was a large increase in the number of flowers, rather than to differences in boll retention. Harvest index, seed size, and percent lint per boll were not affected by CO_2 concentration, although harvest index was affected by the irrigation treatment, so the primary effect of the CO_2 was to simply make bigger plants. There was an increase in fineness of the fibers with CO_2 enrichment in both wet and dry plots but a 6% decrease in fiber length with CO_2 enrichment in the dry plots, so overall changes in fiber quality were minimal.

Measurements of net photosynthesis of individual leaves showed increases in the wet plots of 24 and 51%, and in the dry plots of 32 and 39% for the 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2 treatments, respectively. Although these increases in photosynthesis are indeed substantial, they are not large enough to account for all of the yield increase with CO_2 enrichment.

Measurements of stomatal resistance and of leaf temperature were also made. There was no consistent pattern of stomatal resistance differences with CO_2 concentration in the wet plots, but in the dry plots CO_2 increased stomatal resistance, particularly during times of mild water stress. The leaf temperature data of well-watered cotton showed that under humid conditions (vapor pressure deficit - 1 kPa), the CO_2 affected leaf temperature by less than 1°C. However, as the air became drier, CO_2 caused an increase in leaf temperature so that at a vapor pressure deficit of 4 kPa, leaf temperature was increased by about 2°C by a doubling of CO_2 concentration. These leaf temperature observations are somewhat in conflict with the stomatal resistance data for well-watered cotton, but there were many more temperature data so these are probably more reliable.

Leaf water potential and relative leaf water content were determined several times during the season. These data require more analyses, but preliminary indications are that the CO_2 enriched plants contained more water in their leaf tissues at any given level of leaf water potential.

The water use from the top 800 mm of the soil profile was determined from soil water depletion measurements with neutron apparatus. The water use tended to increase with increasing CO_2 concentration in the Rep I plots, both wet and dry. There was little effect of CO_2 on the Rep II - wet plots, whereas the Rep II - dry plots were very inconsistent. Basically, the CO_2 did not change the water use of cotton per unit of land area much or in a consistent direction. If there was any increase in stomatal resistance and commitant decrease in transpiration per unit of leaf area, the (1) much greater leaf area of CO_2-enriched plants, (2) the higher leaf temperature of CO_2-enriched plants, and (3) the evaporation from the soil surface (which is unaffected by CO_2) all combine to nullify any potential reduction in water requirement. Nevertheless, the 77-92% increase in cotton yield with a doubling of CO_2 while changing water use only a little represents a huge increase in water use efficiency.

An attempt was made to determine the effects of increasing atmospheric CO_2 concentration on the evolution of CO_2 from the soil. Measurements

of soil surface flux and of soil CO_2 concentrations revealed an unexpected result. There was little difference among chambers, but all of the chambers had lower soil CO_2 concentrations than the open field. After the experiment was terminated, about a month passed before soil CO_2 concentrations were again the same inside and outside the chambers. Apparently, the blowers used in the CO_2 enrichment system actually flush CO_2 out of the soil due to increased absolute pressure and pressure fluctuations at the soil surface.

Counts were made of six insect populations caught on sticky traps in the plots. Populations of thrips and of whiteflies were not affected by the CO_2 treatments. However, populations of flea beetle, pink bollworm, leaf hoppers, and a predacious fly in the 650 $\mu\ell\ \ell^{-1}$ CO_2 chamber were decreased to 42%, 59%, 68%, and 22%, respectively, of the numbers in the ambient chamber. The reason for these population decreases is unknown, but these results indicate that insect problems should not become worse and may even be better in a future high-CO_2 world.

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Table 1. Irrigation and rain amounts for the CO_2-cotton 84 experiment.

Date	Day of Year	Source[1]	Wet Plots Rep I	Wet Plots Rep II	Dry Plots Rep I	Dry Plots Rep II
			mm			
27 Mar	87	I	230	230	230	230
30 May	151	I	150	150	150	150
13 Jun	165	I	149	147	0	0
21 Jun	173	I	0	0	150	150
25 Jun	177	R	4	4	4	4
27 Jun	179	I	150	148	0	0
29 Jun	181	R	3	3	3	3
30 Jun	182	R	1	1	1	1
11 Jul	193	I	150	150	150	150
13 Jul	195	R	5	5	5	5
17 Jul	199	R	1	1	1	1
18 Jul	200	R	9	9	9	9
20 Jul	202	R	3	3	3	3
21 Jul	203	R	34	34	34	34
25 Jul	207	I	150	150	0	0
28 Jul	210	R	100[2]	74	74	74
8 Aug	221	I	100	150[3]	150	150
9 Aug	222	R	5	5	5	5
14 Aug	227	R	2	2	2	2
23 Aug	236	I	150	150	0	0
23 Aug	236	R	2	2	2	2
30 Aug	243	I	0	0	150	150
1 Sep	245	R	20	20	20	20
6 Sep	250	I	150	150	0	0
10 Sep	254	R	46	46	46	46
15 Sep	259	R	1	1	1	1
21 Sep	265	R	2	2	2	2
25 Sep	269	R	8	8	8	8
26 Sep	270	R	20	20	20	20
3 Oct	277	R	5	5	5	5
		Totals	1650	1670	1225	1225

[1] I = Irrigation, R = Rain
[2] Estimated because runoff from adjacent field overflowed berm
[3] Berm broke, slight loss of water

Table 2. Petiole nitrate concentrations measured during the CO_2-cotton 1984 experiment.

Date	Day of Year	Rep:	OPEN FIELD I	OPEN FIELD II	CHAMBER CO_2 CONC. AMB I	AMB II	500 I	500 II	650 I	650 II
DRY PLOTS:			ppm NO_3 - N X 10^{-3}							
4 June	156		22.8	26.2	24.2	25.9	27.1	25.1	24.5	23.6
11 June	163		15.1	27.6	22.0	23.6	21.4	18.8	20.8	20.5
18 June	170		18.2	18.2	13.1	13.5	12.6	13.2	18.4	12.7
25 June	177		11.8	11.1	13.0	14.1	7.2	7.7	8.3	7.6
2 July	184		13.5	11.6	13.4	13.7	10.3	7.6	12.4	6.4
9 July	191		9.0	7.9	13.6	10.8	11.3	9.4	10.7	11.1
16 July	198		6.7	7.3	10.8	11.8	7.2	6.3	8.8	8.1
1 August	214		3.1	2.3	7.8	5.5	4.2	3.7	4.4	1.7
20 August	233		2.6	0.7	2.5	2.9	2.0	1.1	2.4	2.6
WET PLOTS:										
4 June	156		31.4	22.0	28.5	26.8	27.4	27.1	29.4	30.2
11 June	163		27.1	26.5	19.7	22.3	19.4	24.5	17.1	24.5
18 June	170		14.1	16.5	18.0	17.5	15.2	13.5	13.7	12.8
25 June	177		13.8	8.4	13.8	13.1	11.0	11.7	11.4	8.7
2 July	184		11.6	9.7	9.8	10.4	9.6	7.6	7.3	-
9 July	191		13.3	7.4	12.1	7.9	8.8	9.6	8.1	8.0
16 July	198		7.3	8.0	10.3	8.0	7.8	4.8	8.1	7.8
1 August	214		1.5	3.3	4.6	3.2	3.4	0.66	1.0	1.5
20 August	233		2.1	4.6	2.4	2.9	1.9	-	1.8	-

Table 3. Daytime, nighttime, and whole day mean CO_2 concentrations and the corresponding standard deviations of the individual observations for the entire season of the CO_2-cotton 1984 experiment.

Condition		Open Field	NOMINAL CHAMBER CONC. Ambient	500	650
		$\mu\ell\ \ell^{-1}$			
Daytime:					
Wet	Rep I	331 ± 38	334 ± 42	506 ± 88	647 ± 84
	Rep II	332 ± 42	340 ± 48	497 ± 42	646 ± 106
Dry	Rep I	333 ± 42	338 ± 42	499 ± 74	654 ± 90
	Rep II	332 ± 40	326 ± 39	498 ± 45	640 ± 116
Nighttime:					
Wet	Rep I	362 ± 53	380 ± 61	539 ± 128	681 ± 101
	Rep II	373 ± 64	394 ± 81	524 ± 641	682 ± 157
Dry	Rep I	379 ± 69	381 ± 65	512 ± 103	696 ± 123
	Rep II	373 ± 59	367 ± 55	523 ± 66	657 ± 115
Whole (24 hr) Day:					
Wet	Rep I	346 ± 48	355 ± 56	521 ± 110	662 ± 94
	Rep II	351 ± 57	365 ± 71	510 ± 55	663 ± 133
Dry	Rep I	355 ± 61	358 ± 58	505 ± 89	673 ± 109
	Rep II	351 ± 54	345 ± 51	509 ± 57	648 ± 116
Overall Means Averaged Over Reps and Water Treatments:					
		350 ± 55	355 ± 60	511 ± 81	662 ± 114

Table 4. Daytime, nighttime, and whole day mean CO_2 concentrations and the corresponding standard deviations of the individual observations from 21 July through 26 October 1983.

CONDITION	OPEN FIELD	NOMINAL CHAMBER CONC. AMBIENT	500	650
	$\mu \ell \ \ell^{-1}$			
Daytime:				
Rep I:	345 ± 42	335 ± 38	500 ± 48	640 ± 104
Rep II:	343 ± 40	336 ± 37	509 ± 85	634 ± 107
Nighttime:				
Rep I:	399 ± 63	380 ± 49	517 ± 61	653 ± 101
Rep II:	391 ± 52	375 ± 45	569 ± 130	648 ± 89
Whole (24 hr) day:				
Rep I:	371 ± 59	357 ± 49	508 ± 55	646 ± 103
Rep II:	366 ± 52	355 ± 46	538 ± 112	641 ± 99
Overall means averaged over reps:				
	368 ± 56	356 ± 47	523 ± 90	643 ± 101

Table 5. Seed cotton yield, total dry matter production, and other yield data for the CO_2-cotton 1984 experiment.

	CO_2 Concentration in Chambers ($\mu\ell/\ell$)															
	OPEN FIELD				AMBIENT				500				650			
	W		D		W		D		W		D		W		D	
Item	I	II	I	II	I	II	I	II	I	II	I	II	I	II	I	II
Plants/m^2	5.2	9.0	9.0	9.0	8.7	10.3	11.3	8.3	8.7	10.0	8.3	9.3	8.7	9.0	10.7	10.0
Plant Height (mm)	767	698	767	690	1085	993	815	782	1033	1080	890	852	1082	1147	1040	967
No. Bolls/m^2	88	119	106	145	110	132	112	141	176	181	158	165	215	198	221	214
Plant Top Dry Wt. (g/m^2)	897	1553	1075	1206	1272	1553	1049	1369	2011	2247	1267	1592	2744	2792	2320	1846
Root Dry Wt. (g/m^2)	80	113	116	120	114	137	105	110	180	180	125	160	210	198	203	146
Total	977	1666	1191	1326	1386	1690	1154	1479	2191	2427	1392	1752	2954	2990	2523	1992
Average	1321		1259		1538		1316		2309		1572		2972		2257	
Rel. CO_2 Effect	0.87		0.96		1.00		1.00		1.50		1.19		1.93		1.71	
Lint Weight (g/m^2)	134	204	218	210	170	221	175	222	269	305	256	269	384	367	357	348
Seed Weight (g/m^2)	223	320	360	327	284	371	300	373	437	494	426	462	672	609	644	544
% Lint	38	39	38	39	37	37	37	37	38	38	38	37	36	38	36	39
Seed Cotton Wt. (g/m^2)	357	524	578	537	454	592	475	595	706	799	682	731	1056	976	1001	892
Avg. Seed Cotton	441		558		523		535		753		707		1016		947	
Rel. CO_2 Effect	0.84		1.04		1.00		1.00		1.44		1.32		1.94		1.77	
Avg. Lint Wt.	169		214		196		199		287		263		376		353	
Rel. CO_2 Effect	0.86		1.08		1.00		1.00		1.46		1.32		1.92		1.77	
Seed Index (g/100 seeds)	9.55	8.86	9.27	8.58	9.35	10.01	9.68	9.75	9.39	9.73	10.42	10.12	10.48	10.11	10.01	9.56
Fiber Length (in.)	1.03	0.98	1.07	0.98	1.06	1.13	1.04	1.09	1.12	1.09	1.06	1.00	1.06	1.11	1.08	0.98
Fiber Fineness	4.83	4.45	4.79	4.85	4.14	4.75	5.18	4.99	4.75	5.05	5.48	5.05	5.00	5.18	5.05	5.48
Harvest Index (%)	40	34	54	45	36	38	45	43	35	36	54	46	38	35	43	48

Table 6. Seed Cotton (seed + lint) yield of field-grown CO_2-enriched cotton at two levels of irrigations.

Total Water (cm)	Irrigation cycle	CO_2 (μl^{-1}) AMB	500	650
		-------	kg/ha	---
166	Wet-14 days	5230 (1.00)	7530 (1.44)	10160 (1.94)
152	Dry-21 days	5350 (1.00)	7070 (1.32)	9460 (1.77)

Table 7. Components of yield for treatments in the 1984 Experiment. "Flowers" are total blossoms formed up to Aug. 27. "Retention" is the percentage of these blossoms which resulted in harvestable bolls; and "Lint/boll" is average weight of harvested lint per boll. The increase in "Flowers" was the major component of the yield increase resulting from CO_2 enrichment.

1984 COMPONENTS OF YIELD

CO_2 Treatment	FLOWERS ($/m^2$)		RETENTION (%)		LINT/BOLL (g)	
($\mu\ell\ \ell^{-1}$)	Wet	Dry	Wet	Dry	Wet	Dry
350	305	301	35.4	36.0	1.61	1.57
500	477	400	34.2	36.1	1.66	1.62
650	543	529	36.4	38.2	1.82	1.62

Table 8. Cumulative numbers of flowers produced by various dates during 1984 as influenced by CO_2 concentration and enclosure in open-top chambers. Data are averages of 2 replications and 2 irrigation levels ± SE.

		CO_2 Conc. in chambers ($\mu\ell\ \ell^{-1}$)		
	Open	Ambient	500	650
Julian date	Number of flowers per m^2			
167	1± 1	0	0	0
174	11± 3	2± 1	2± 1	7± 5
181	36± 9	8± 3	9± 2	28±17
188	74±13	37± 7	49± 6	78±23
195	136±12	95±14	139±12	186±17
202	171± 5	143±11	208±20	271± 5
209	191± 6	193±12	280±29	356±16
216	201±11	224±11	326±33	405±27
223	220±11	273±10	393±30	477±29
230	226±11	287± 8	423±34	508±29
237	231±12	301±10	437±37	532±29

Table 9. Cumulative percentage of bolls retained to the end of the season that appeared as flowers by various dates during 1984 as influenced by CO_2 level and enclosure in open-top chambers. Data are averages of 2 replications and 2 irrigation levels ± SE.

		CO_2 Conc. in chambers ($\mu\ell\ \ell^{-1}$)		
	Open	Ambient	500	650
Julian date	------- Percentage of bolls retained -------			
167	-	-	-	-
174	85.1±7.1	64.0±7.4	84.2±8.2	75.2±17.7
181	70.4±3.8	62.1±5.1	59.8±6.3	75.2±9.2
188	51.4±1.2	33.4±3.7	35.0±2.7	41.8±5.5
195	50.0±5.9	40.2±5.2	35.0±4.9	39.7±3.5
202	50.2±3.4	42.4±2.0	35.8±3.2	40.0±2.8
209	47.4±2.3	38.6±1.9	32.4±2.5	35.5±2.5
216	46.6±2.0	38.0±1.1	32.8±1.5	35.4±1.7
223	46.7±1.9	36.8±0.9	33.9±1.0	36.4±1.9
230	47.0±1.9	37.1±1.2	35.4±1.8	37.6±1.9
237	48.0±2.4	35.7±1.0	35.1±1.8	37.3±2.0

Table 10. Cumulative numbers of bolls set from flowers that appeared by various dates during 1984 as influenced by CO_2 level and enclosure in open-top chambers. Data are averages of 2 replications and 2 irrigation levels ± SE.

		CO_2 Conc. in chambers ($\mu\ell\ \ell^{-1}$)		
	Open	Ambient	500	650
Julian date	-------	Number of bolls per m^2		-------
167	1±1	0	0	0
174	9±3	1±0	2±1	5±4
181	26±7	5±2	6±2	20±11
188	38±7	13±4	17±2	33±11
195	67±5	39±9	49±9	73±7
202	86±7	61±8	75±11	108±6
209	91±7	75±8	91±12	127±10
216	94±7	86±6	107±11	144±12
223	102±7	101±5	133±6	173±10
230	106±7	107±6	148±6	190±4
237	111±7	108±6	152±7	196±2

Table 11. Percentage change in midday net photosynthesis rate of cotton in the CO_2 - cotton 84 experiment. Data were collected during several irrigation cycles from 17 July until 17 August 1984. The sample size (N_{days}) refers to the number of days for which the indicated comparison could be made while the sample size (N_{leaves}) indicates the number of individual leaf observations which went into that comparison.

	WET				DRY			
Comparison	% Change	STD Error	N_{days}	N_{leaves}	% Change	STD Error	N_{days}	N_{leaves}
Ambient Chamber vs Open Field	+18.7	± 8.9	(16)	(94)	+15.3	± 6.2	(17)	(100)
500 $\mu\ell\ \ell^{-1}$ vs Ambient	+23.7	± 5.2	(16)	(93)	+31.5	± 8.7	(17)	(95)
650 $\mu\ell\ \ell^{-1}$ vs Ambient	+50.8	± 5.9	(17)	(93)	+39.1	± 9.4	(17)	(93)

Table 12. Total number of insects collected on sticky traps placed in open field, ambient, 500 and 650 $\mu \ell\ \ell^{-1}$ carbon dioxide enriched chambers in cotton at Phoenix, Arizona. 1984.

Insect	Open	CO_2 Conc. in Chambers ($\mu \ell\ \ell^{-1}$) Ambient	500	650
Flea beetle	371 a	376 a	240 b	160 c
Pink bollworm	497 a	238 b	199 b	141 c
Leafhoppers	1234 a	716 b	565 c	490 c
Predaceous fly	2925 a	403 b	190 c	90 d
Sweetpotato whitefly	4044 a	3905 ab	3299 b	3769 ab
Thrips	6313 a	7818 a	6100 a	6645 a

a/ Totals in a row not followed by the same letter are significantly different; paired t-tests, P = 0.10.

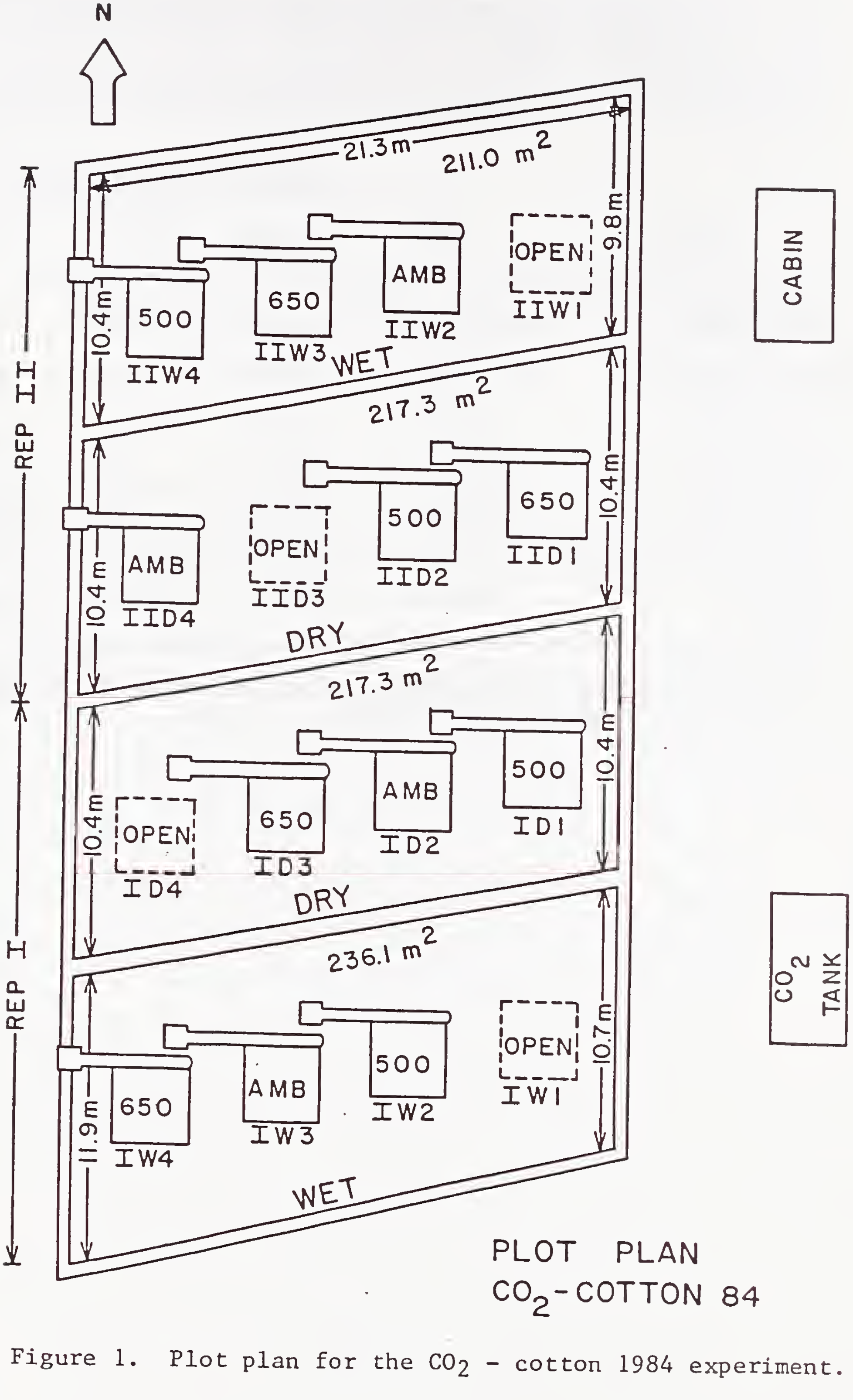

Figure 1. Plot plan for the CO_2 - cotton 1984 experiment.

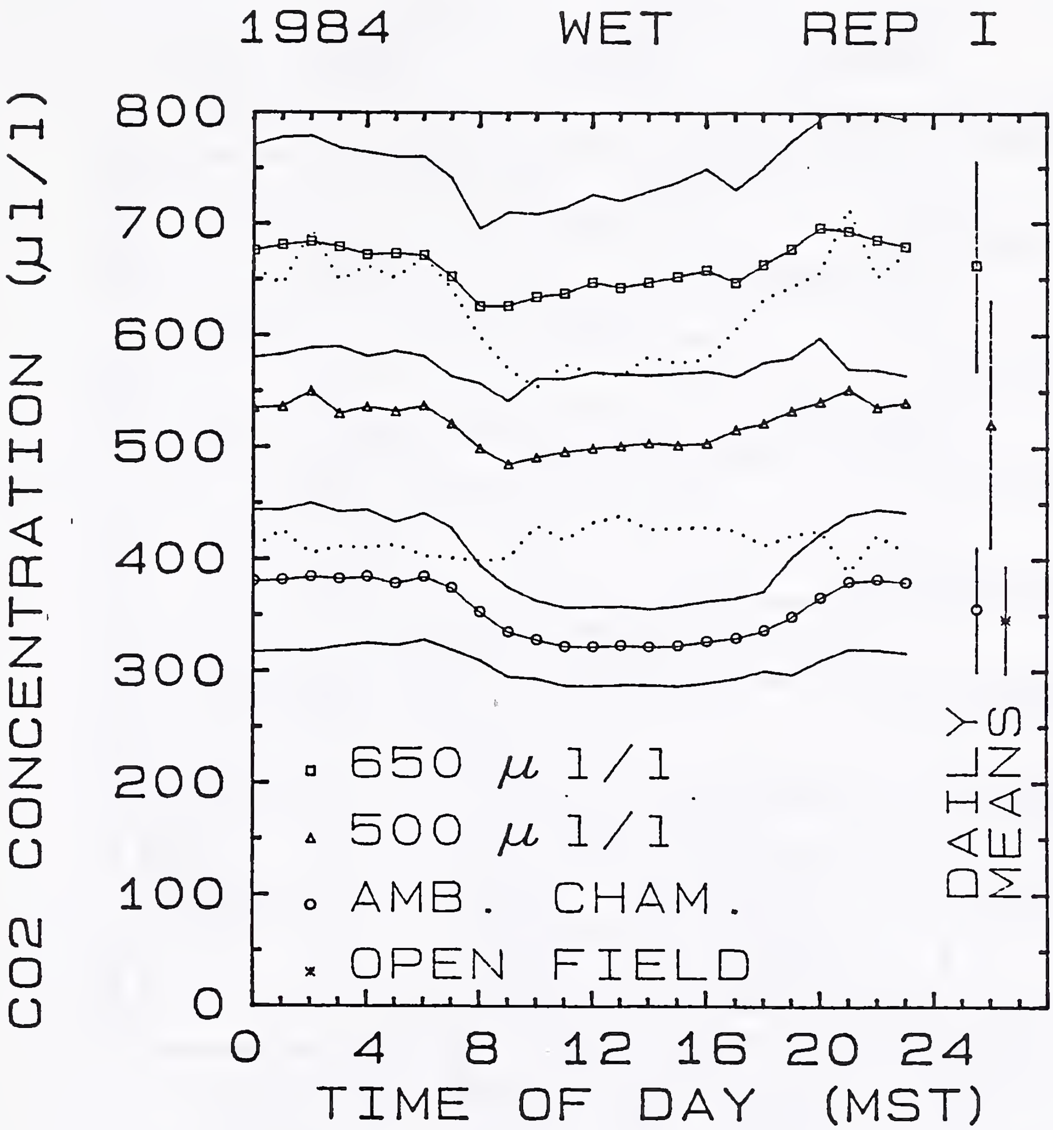

Figure 2. Diurnal pattern of mean CO_2 concentration for the Rep I - wet chambers in 1984. The lower and upper pairs of solid lines are the standard deviation of the individual observations for the ambient and "650" chambers respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the 3 chambers and the open field plot.

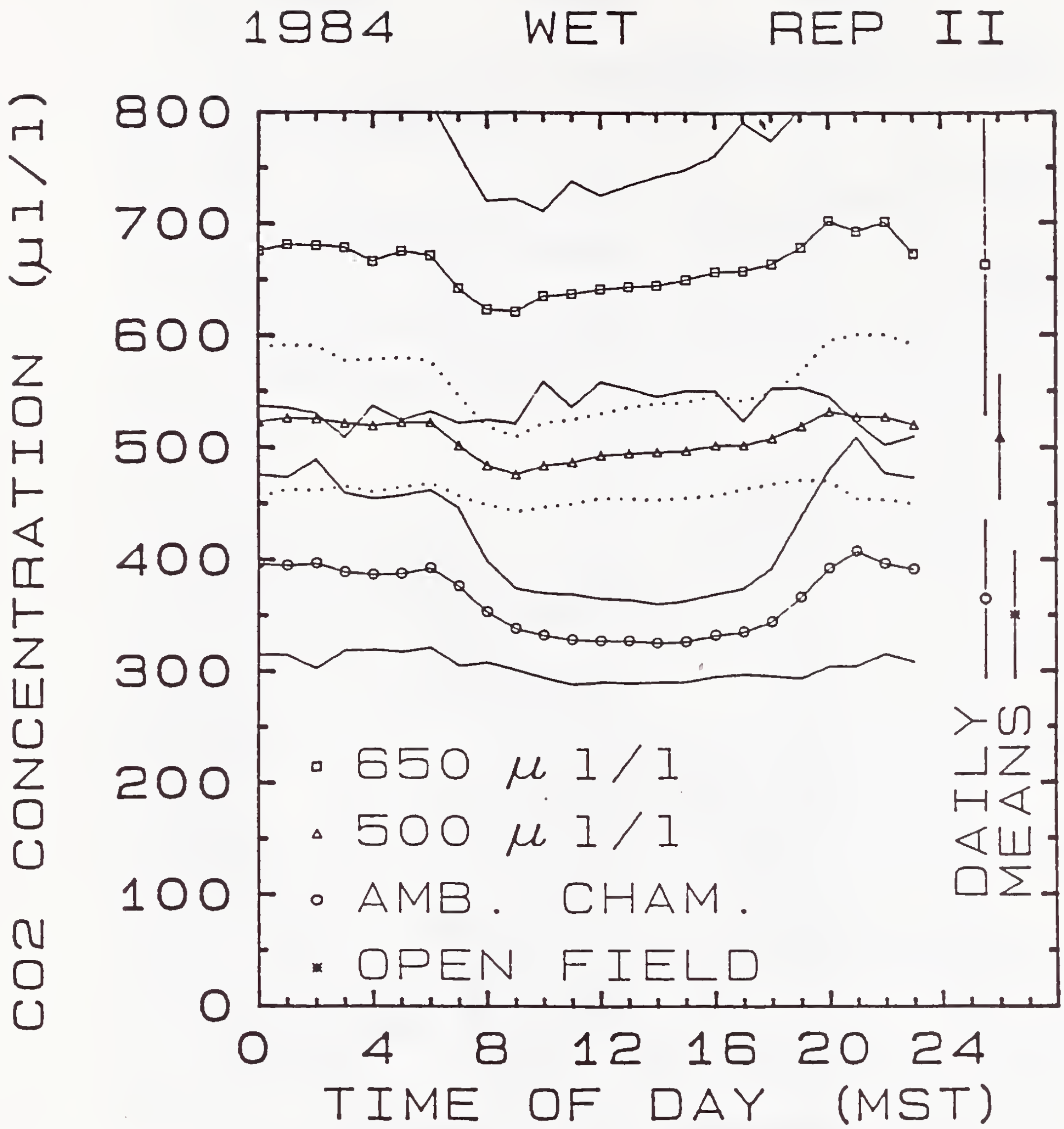

Figure 3. Diurnal pattern of mean CO_2 concentration for the Rep II - wet chambers in 1984. The lower and upper pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the 3 chambers and the open field plot.

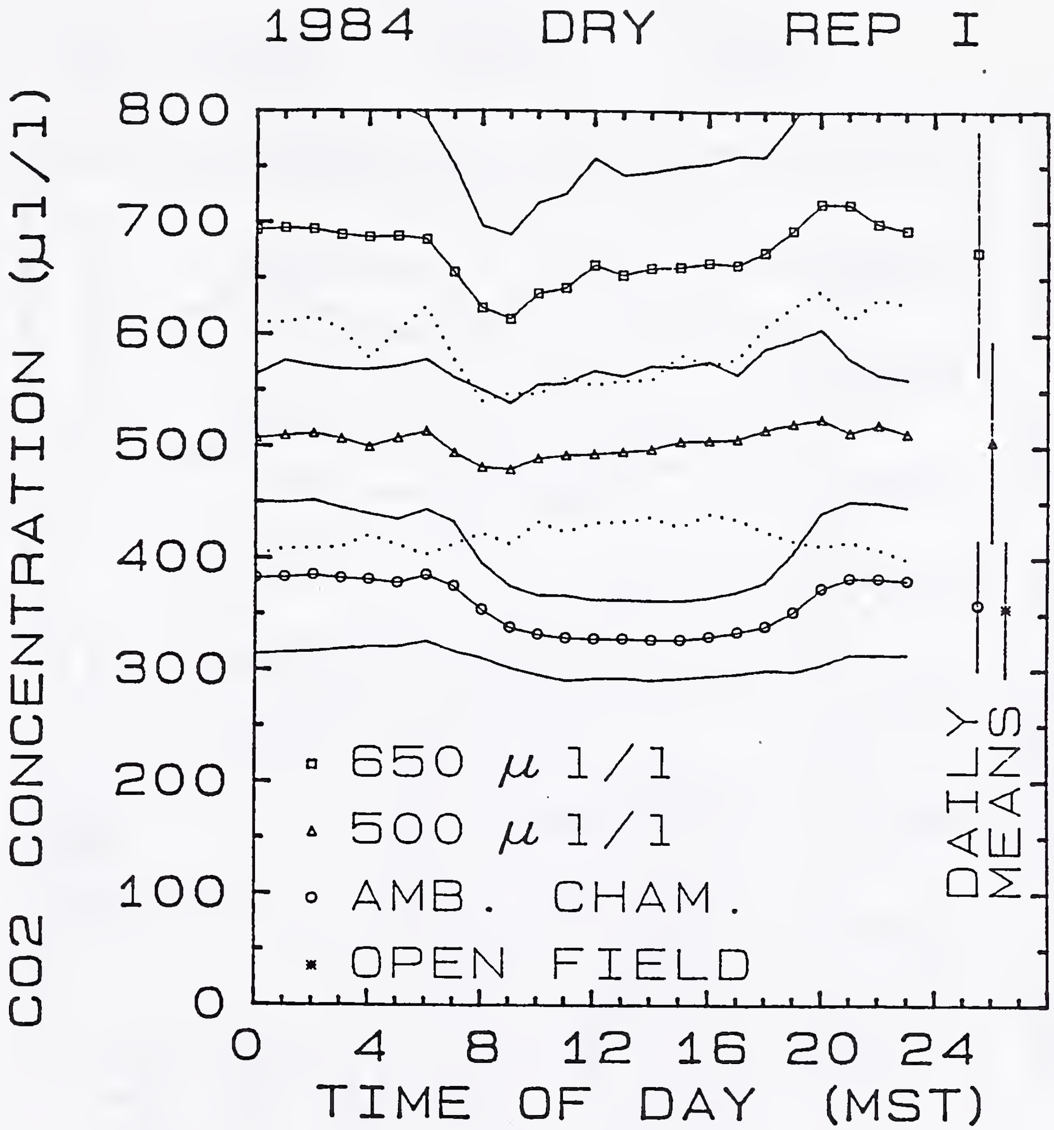

Figure 4. Diurnal pattern of mean CO_2 concentration for the Rep I - dry chambers in 1984. The lower and upper pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the 3 chambers and the open field plot.

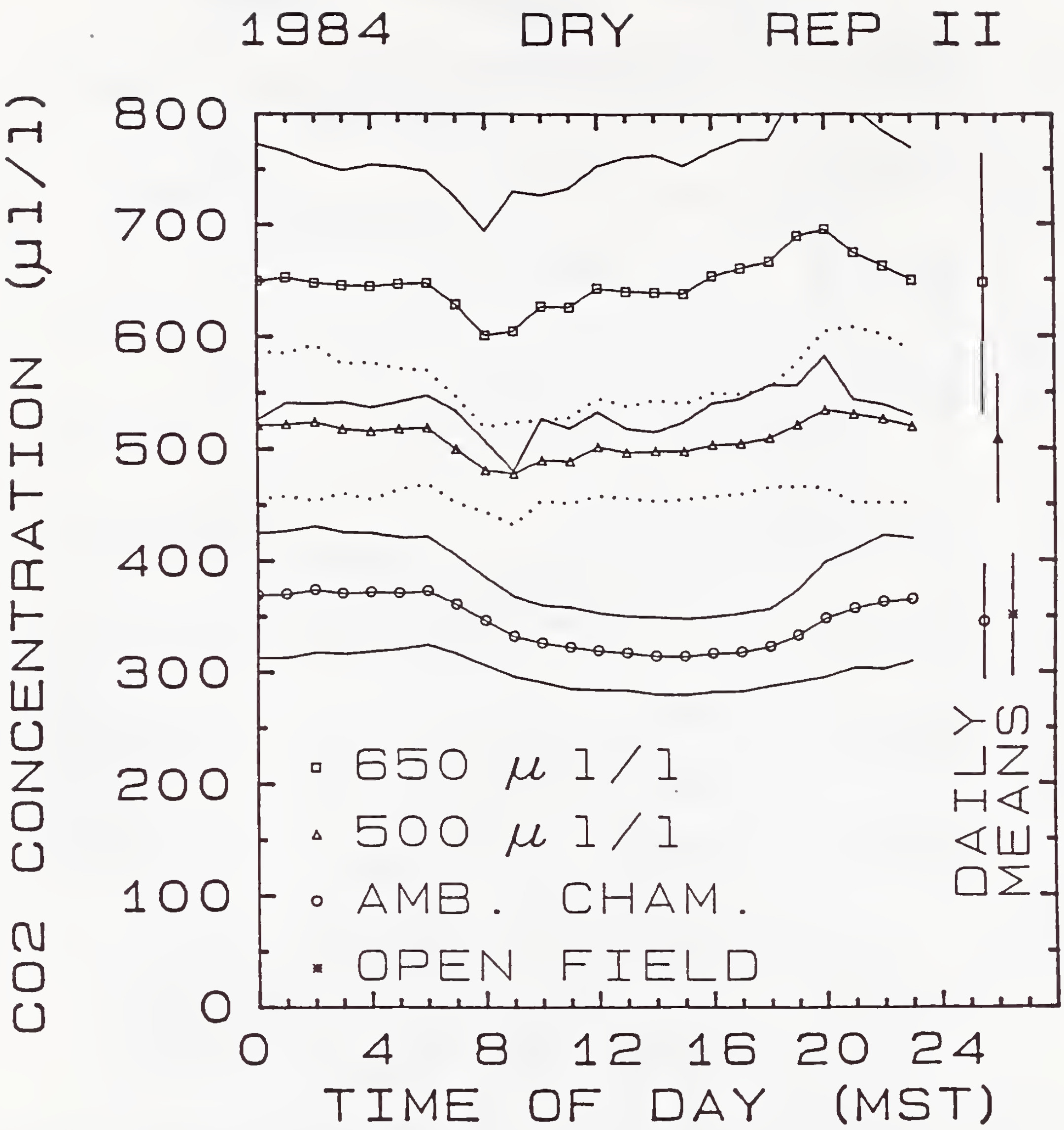

Figure 5. Diurnal pattern of mean CO_2 concentration for the Rep II - dry chambers in 1984. The lower and upper pairs of solid lines are the standard deviation of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the 3 chambers and the open field plot.

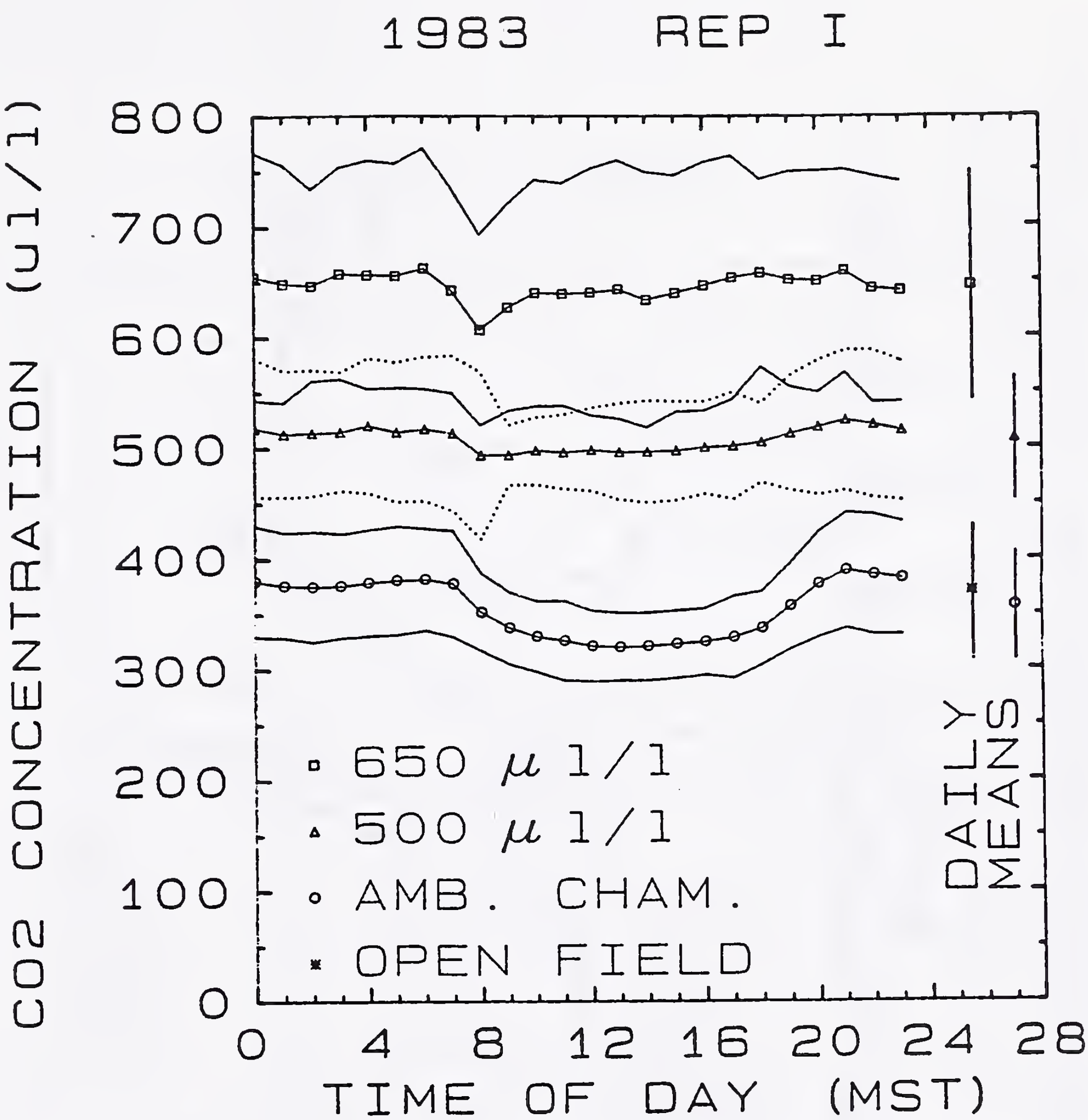

Figure 6. Diurnal pattern of mean CO_2 concentration for the Rep I chambers in 1983. The lower and upper pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the 3 chambers and the open field plot.

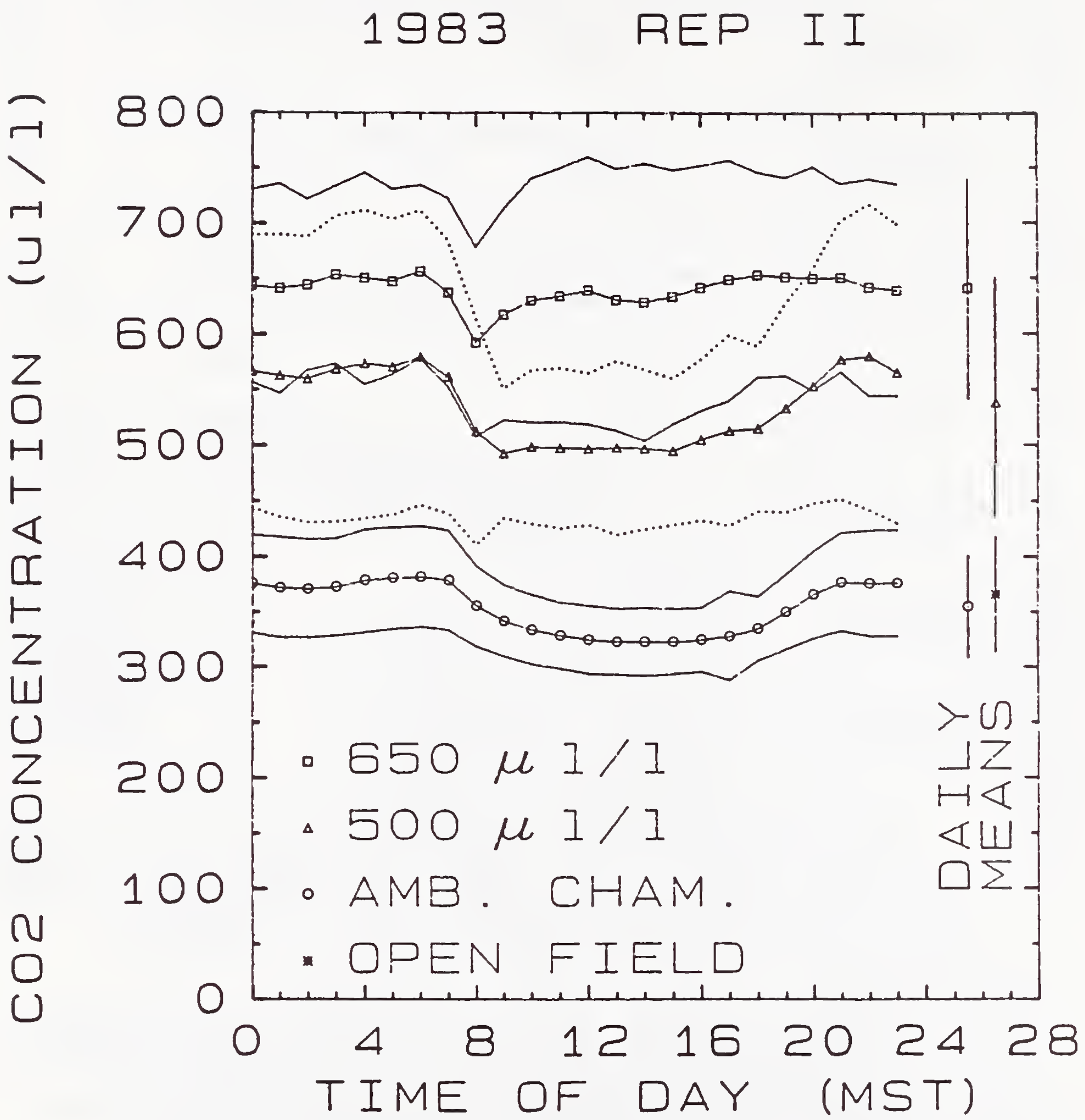

Figure 7. Diurnal pattern of mean CO_2 concentration for the Rep II chambers in 1983. The lower and upper pairs of solid lines are the standard deviations of the individual observations for the ambient and "650" chambers, respectively. The pair of dotted lines are the standard deviations of the "500" chamber. On the right are the all day means and standard deviations for the 3 chambers and the open field plot.

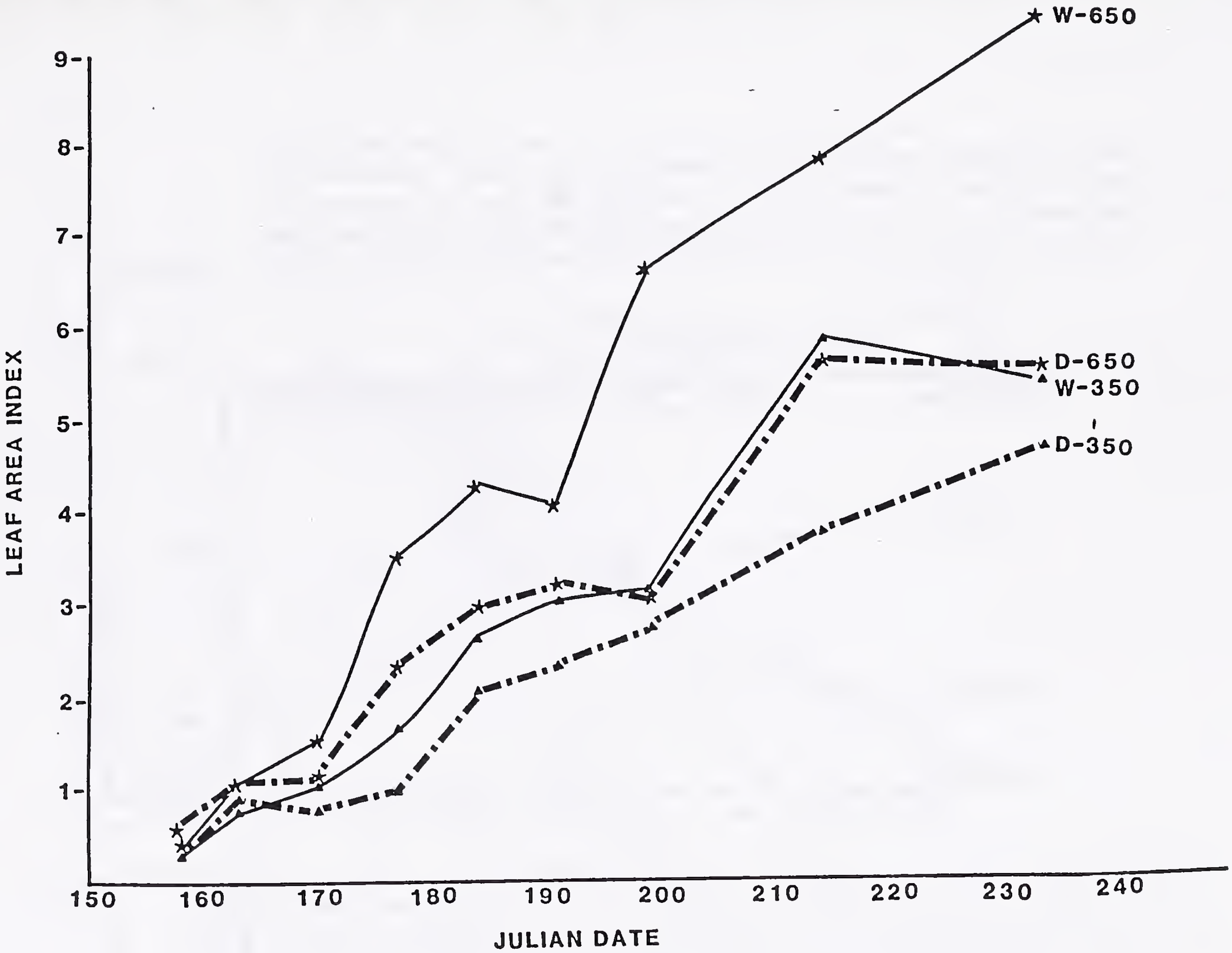

Figure 8. Average leaf area index of plants grown in Ambient (350) and enriched (650) CO_2. The W and D designate the wet and dry treatments, respectively. Leaf area was determined by destructive samples of three plants from each replication on each date shown. (The data for the "500" treatment was intermediate between the "350" and "650" treatments.)

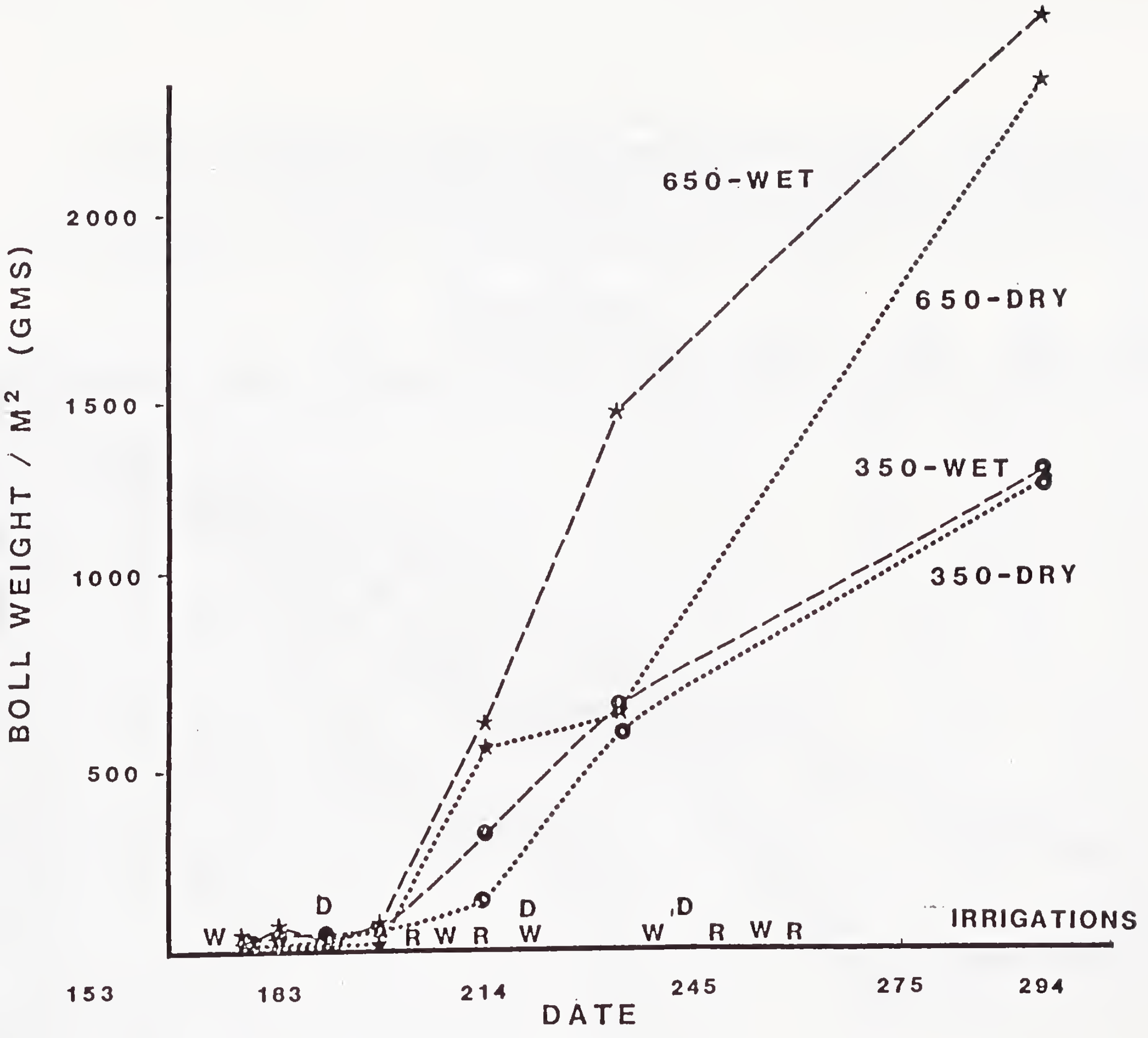

Figure 9. Accumulation of dry weight of bolls per M^2 of standing crop in the "350" and "650"-wet (W) and -dry (D) treatments. Dates of rain events (R) and irrigations for the W and D treatments were as indicated. Data are averages of destructive samples of the three plants from each replication on each date.

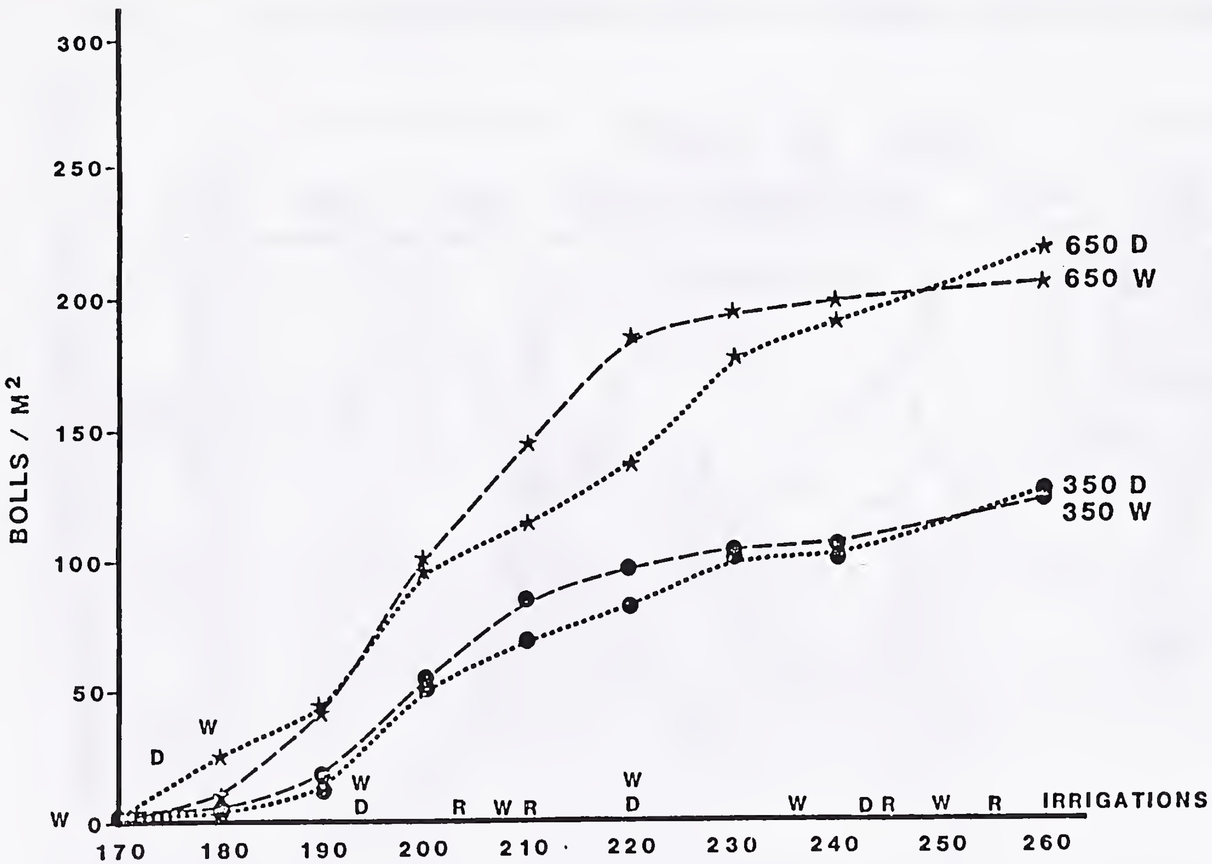

Figure 10. Average number of harvested bolls per M^2 that were present on the plants as the 1984 season progressed. Data were obtained by daily tagging of white blooms throughout the season and counting the number of bolls from each date in the final harvest. For dates when no tags were applied, the the boll loading was assumed to be the average of the dates immediately before and after it. Dates of rain events (R) and irrigation for the wet (W) and dry (D) treatments were as indicated. Note the additional boll loading which occurred in the dry treatment after rain events on day 205 and 210.

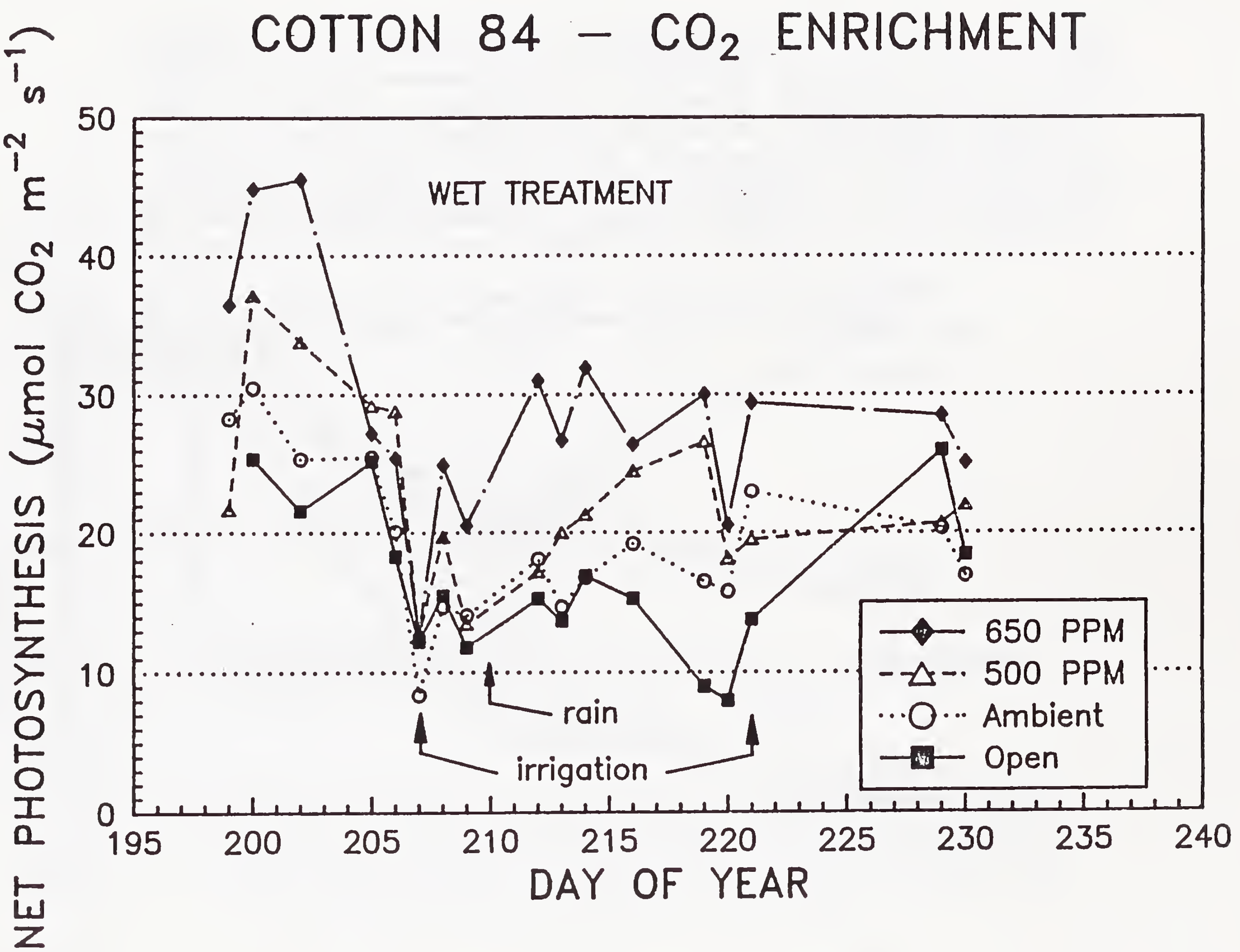

Figure 11. Average net photosynthesis rates for cotton in the wet treatment.

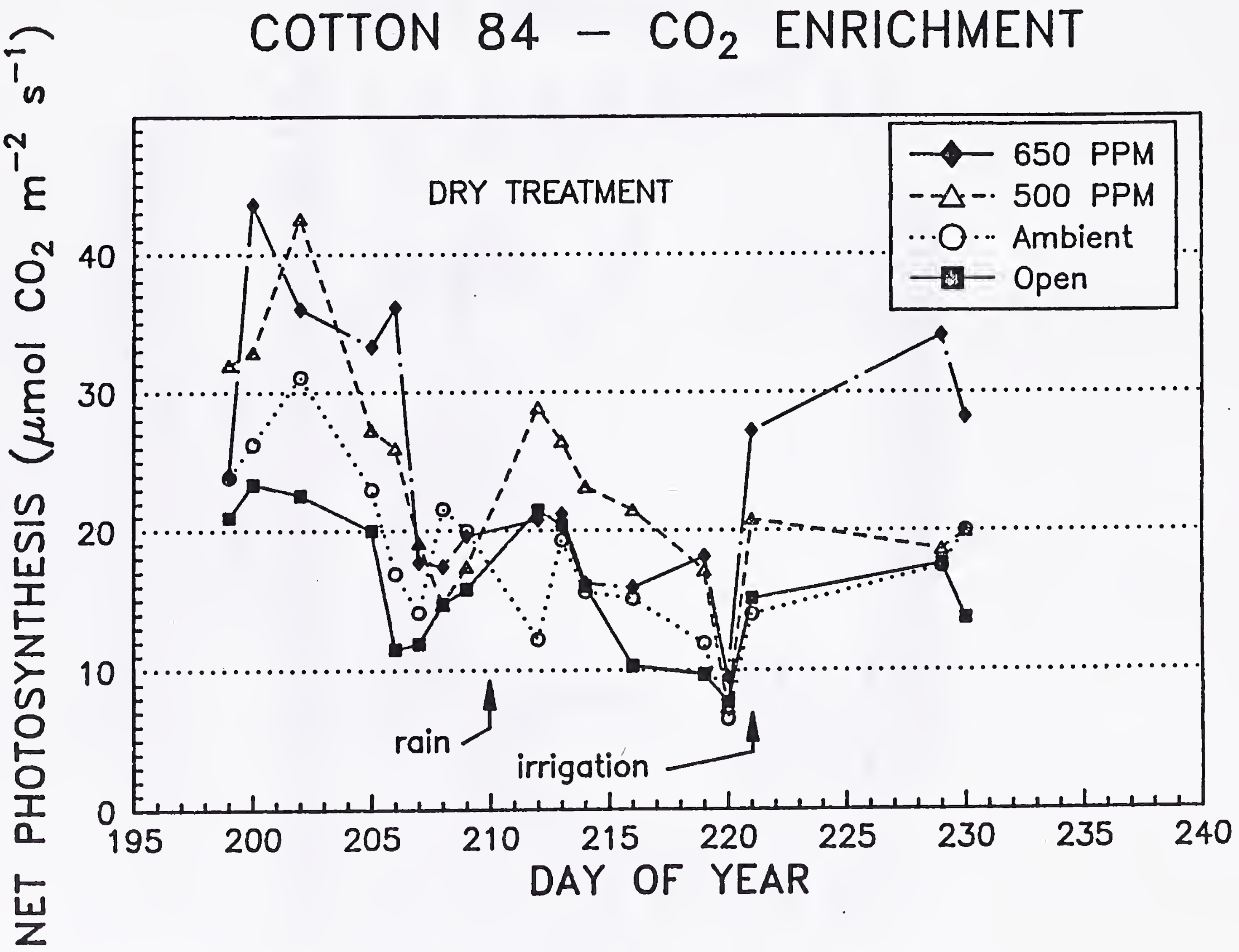

Figure 12. Average net photosynthesis rates for cotton in the dry treatment.

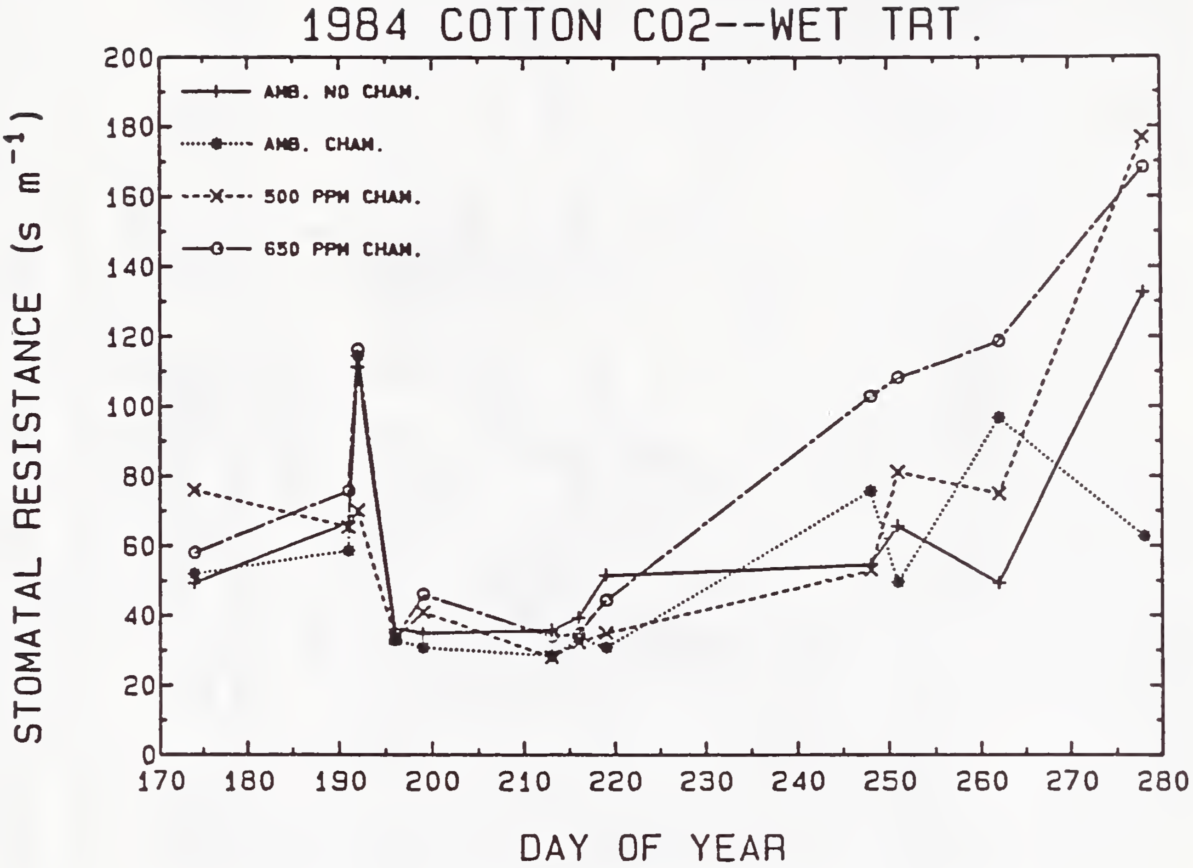

Figure 13. Stomatal resistance of well-watered cotton at ambient, 500 and 650 μℓ ℓ$^{-1}$ CO_2 concentration levels.

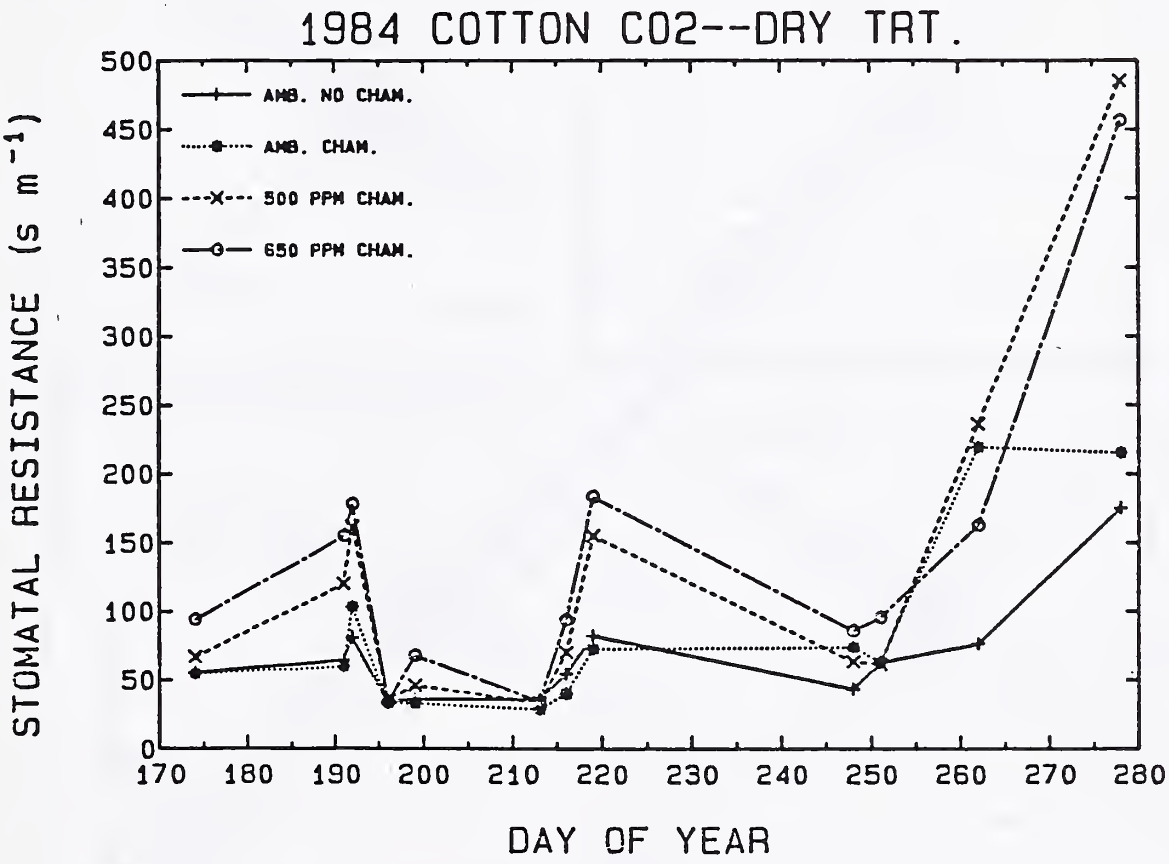

Figure 14. Stomatal resistance of water stressed cotton at ambient, 500 and 650 $\mu\ell\ \ell^{-1}$ CO_2 concentration levels.

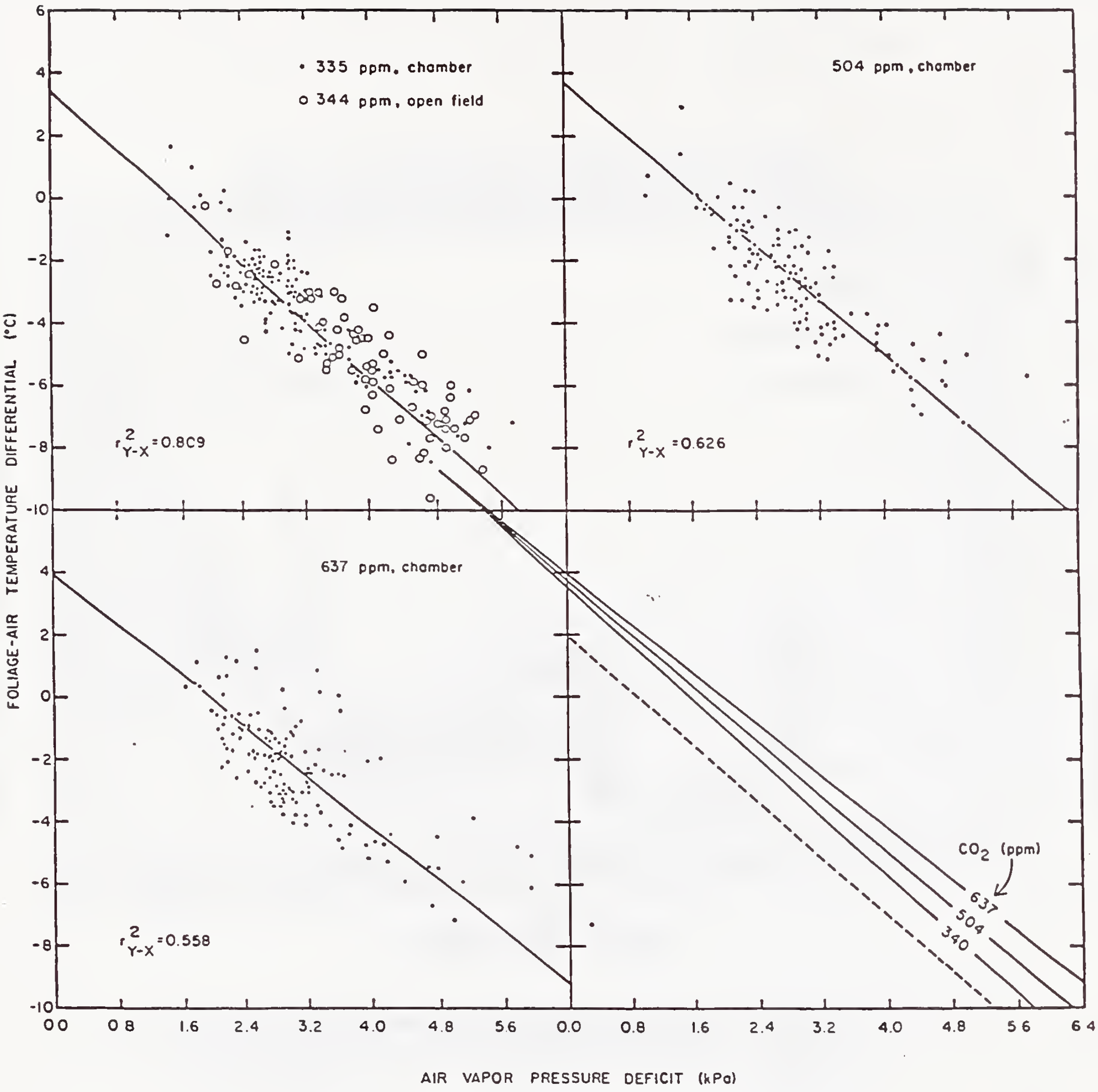

Figure 15. Foliage minus air temperature versus vapor pressure deficit for the ambient (335-344 µℓ ℓ$^{-1}$), "500" (504 µℓ ℓ$^{-1}$), and "650" (637 µℓ ℓ$^{-1}$) CO_2 treatments from the 1983 experiment. All of the data are for non-water-stressed Deltapine 70 cotton. The lines were fitted by regression but forced through a common point, and they are reproduced for comparison in the lower right graph.

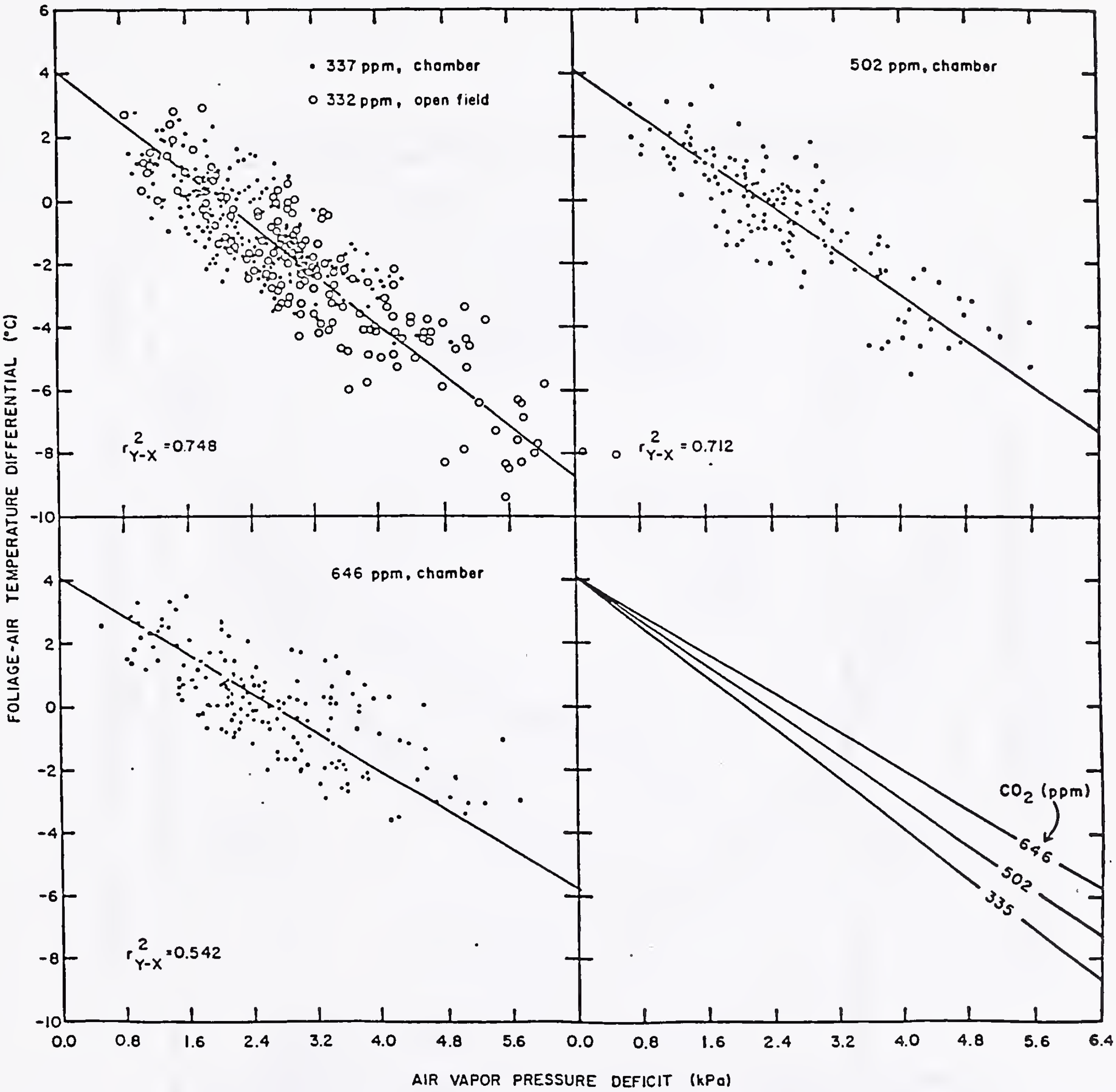

Figure 16. Foliage minus air temperature versus vapor pressure deficit for the ambient (337-332 µℓ ℓ$^{-1}$), "500" (503 µℓ ℓ$^{-1}$), and 650 (646 vℓ ℓ$^{-1}$) CO_2 treatments from the 1984 experiment. All of the data are for non-water-stressed Deltapine 62 cotton. The lines were fitted by regression but forced through a common point, and they are reproduced for comparison in the lower right graph.

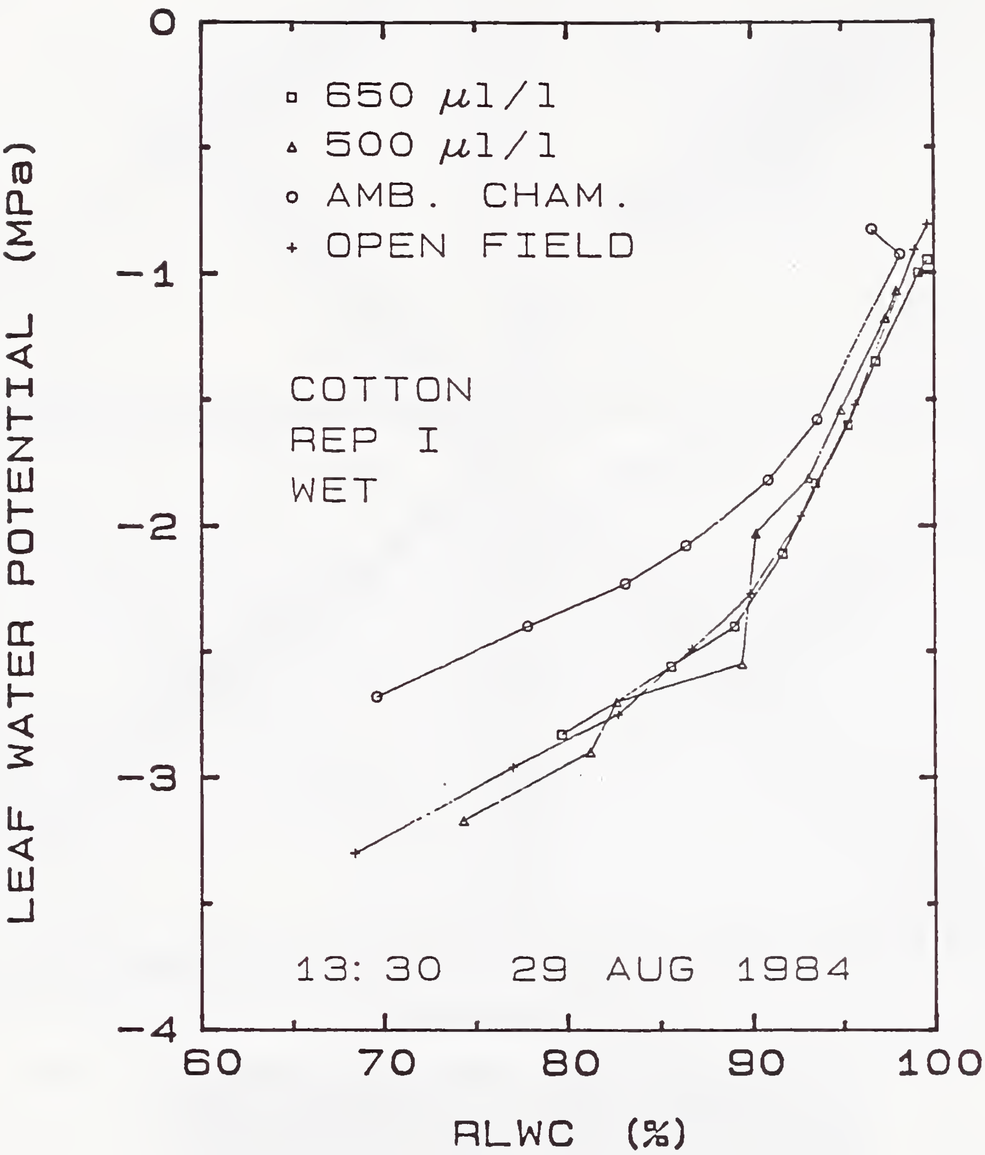

Figure 17. Leaf water potential versus relative leaf water content for the Rep I - wet cotton leaves sampled at 13:30 on 29 August 1984, 1 week after irrigation.

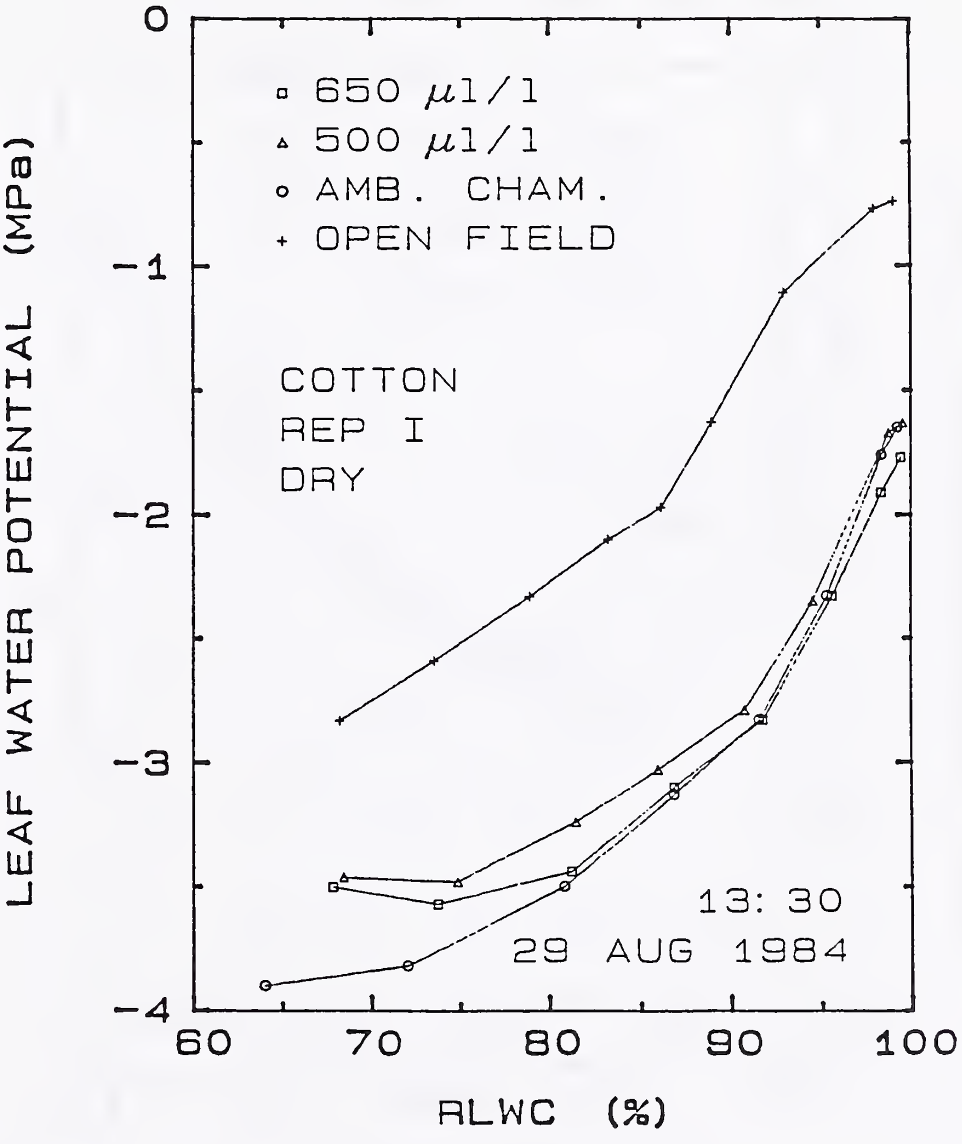

Figure 18. Leaf water potential versus relative leaf water content for the Rep I - dry cotton leaves sampled at 13:30 on 29 August 1984, 3 weeks after irrigation.

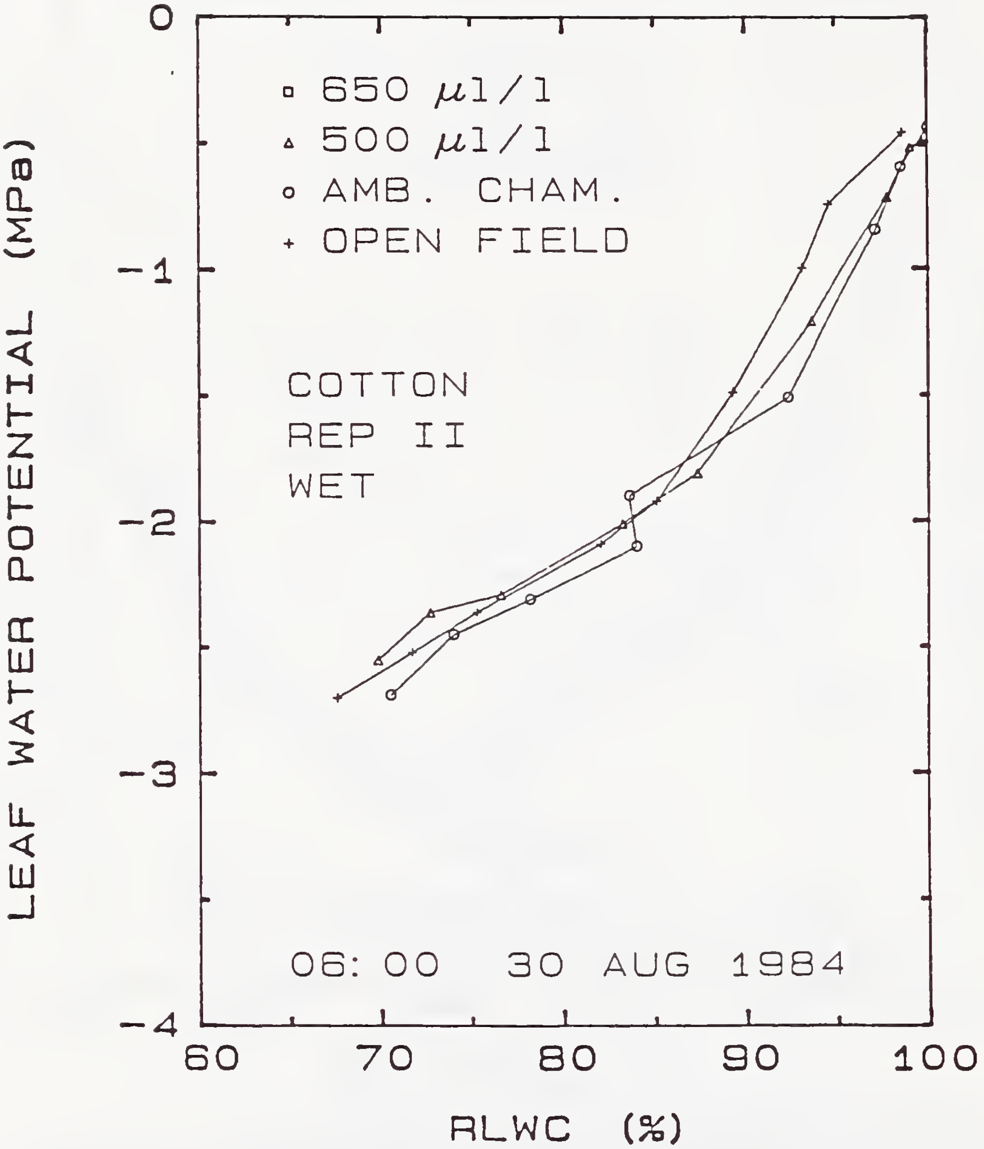

Figure 19. Leaf water potential versus relative leaf water content for the Rep II - wet cotton leaves sampled at 06:00 30 August 1984, 1 week after irrigation.

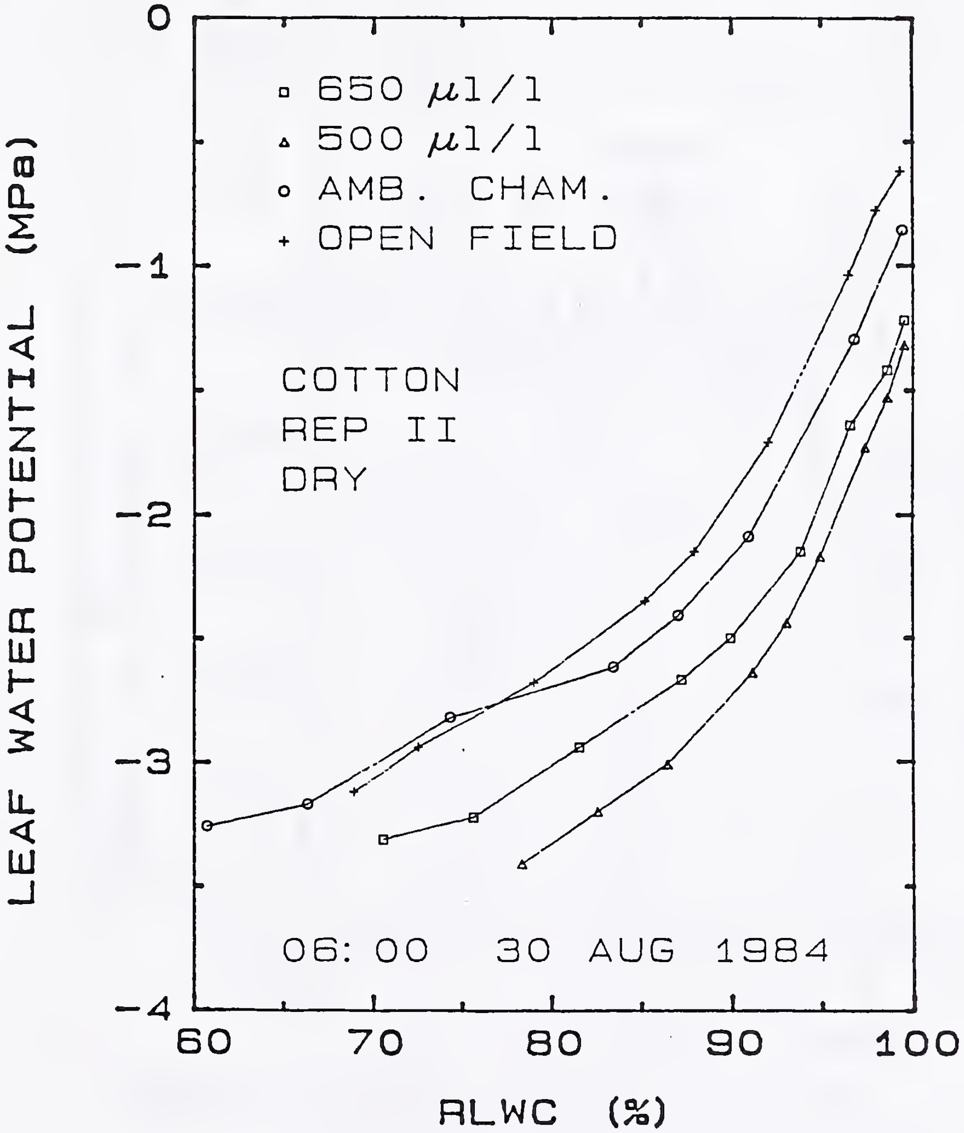

Figure 20. Leaf water potential versus relative leaf water content for the Rep II - dry cotton leaves sampled at 06:00, 30 August 1984, 3 weeks after irrigation.

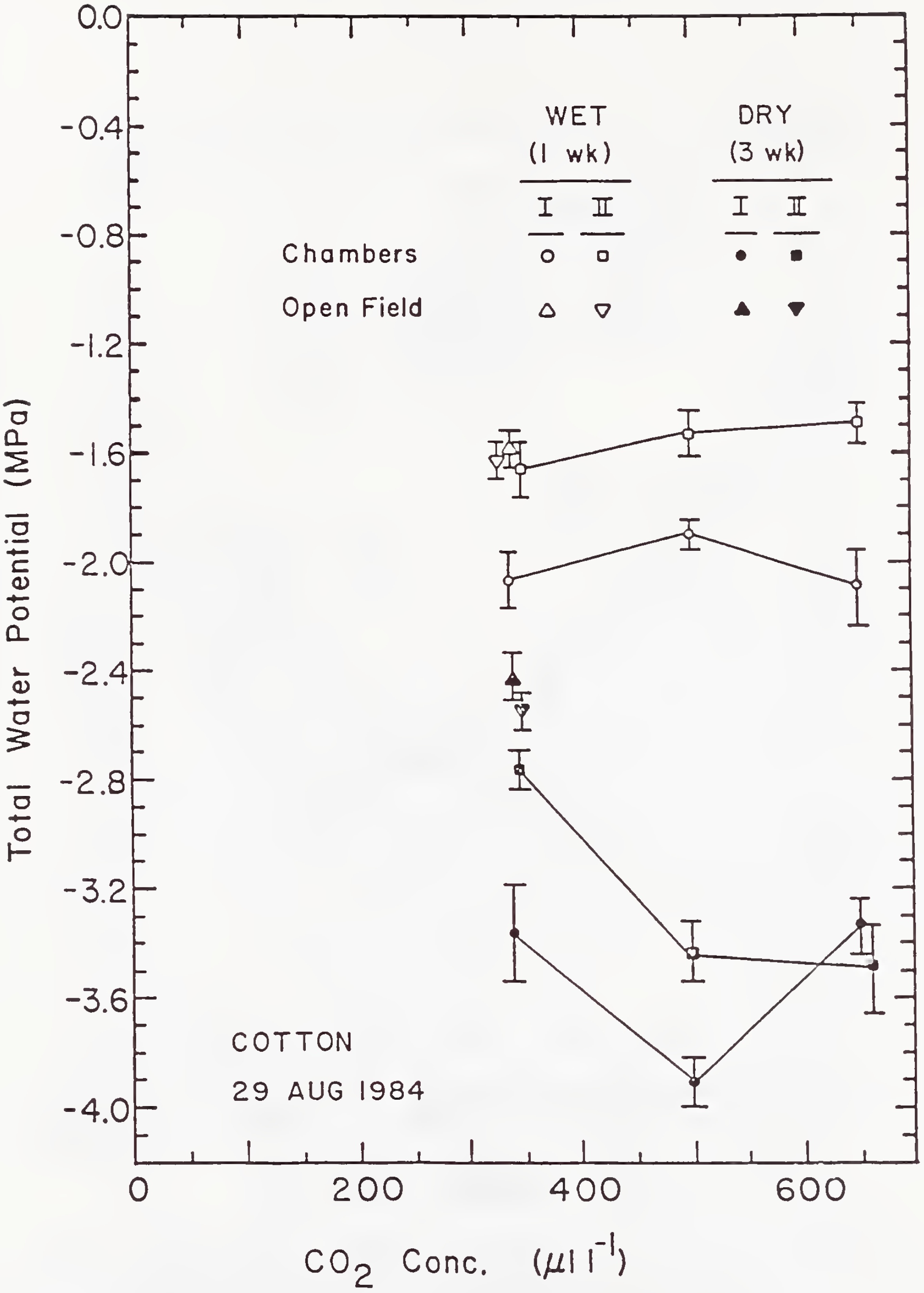

Figure 21. Total leaf water potential of leaves in the field versus CO_2 concentration for the Rep I and II, wet and dry plots at midafternoon on 29 August 1984. The wet and dry plots had been irrigated 1 and 3 weeks, respectively, prior to sampling.

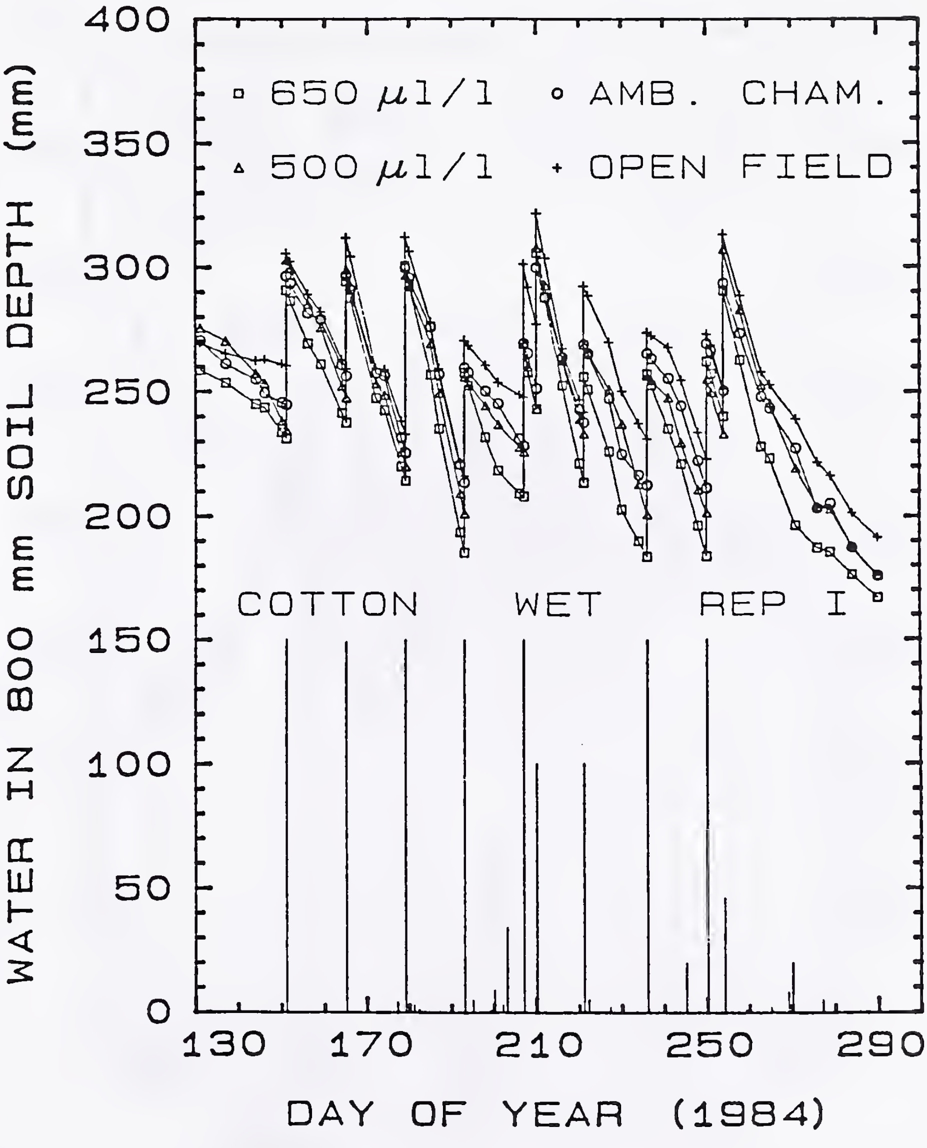

Figure 22. Total water content in the top 800 mm of soil of the Rep I - wet plots against day of year. Also shown are the amounts of irrigation and rainfall (amounts less than 150 mm).

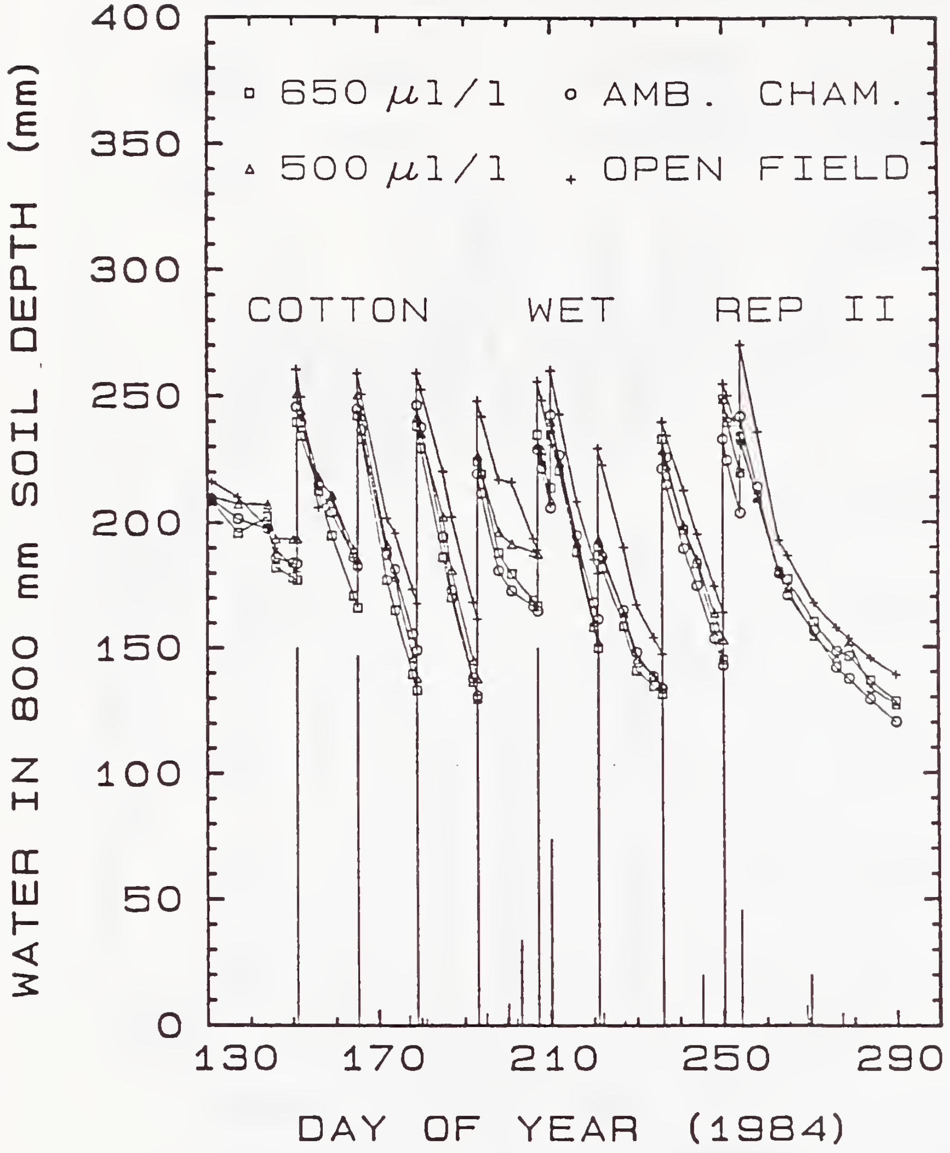

Figure 23. Total water content in the top 800 mm of soil of the Rep II - wet plots against day of year. Also shown are the amounts of irrigation and rainfall (amounts less than 150 mm).

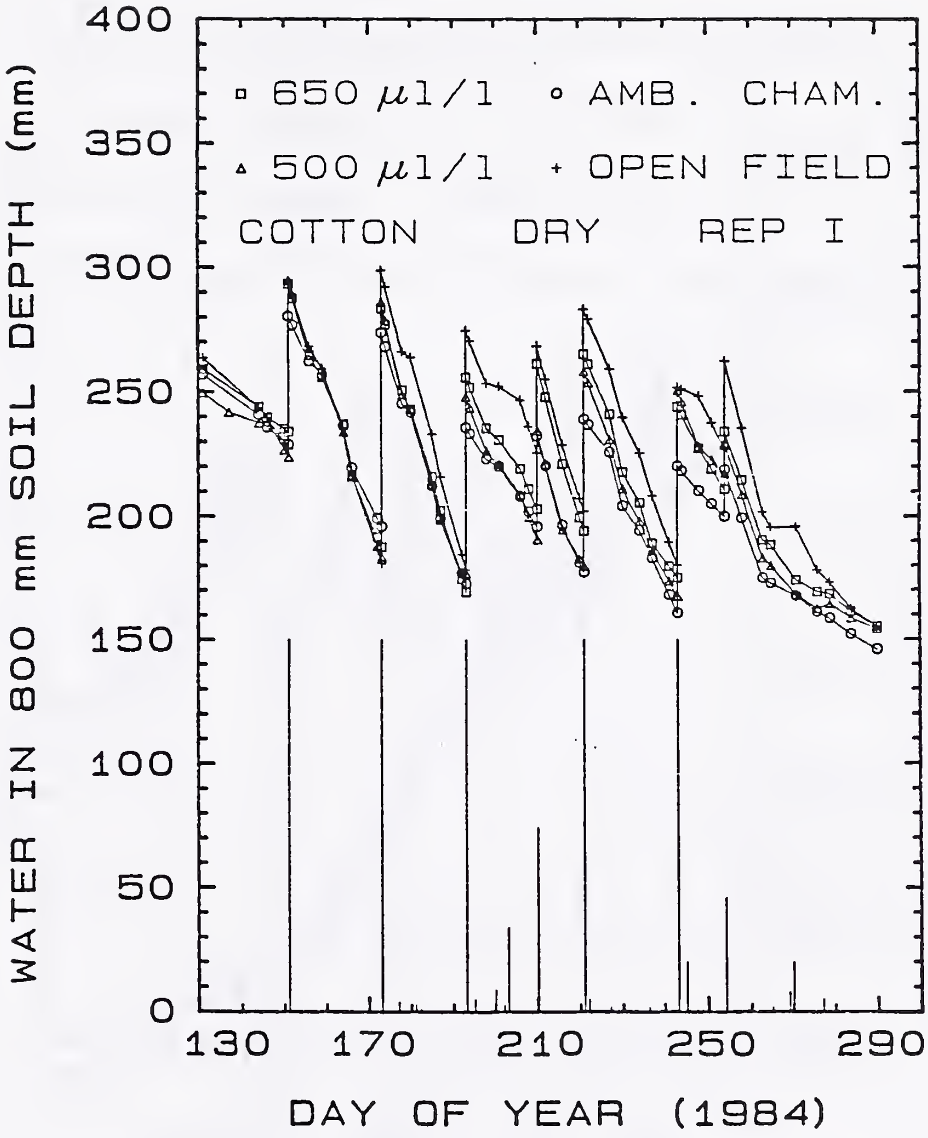

Figure 24. Total water content in the top 800 mm of soil of the Rep I - dry plots against the day of year. Also shown are the amounts of irrigation and rainfall (amounts less than 150 mm).

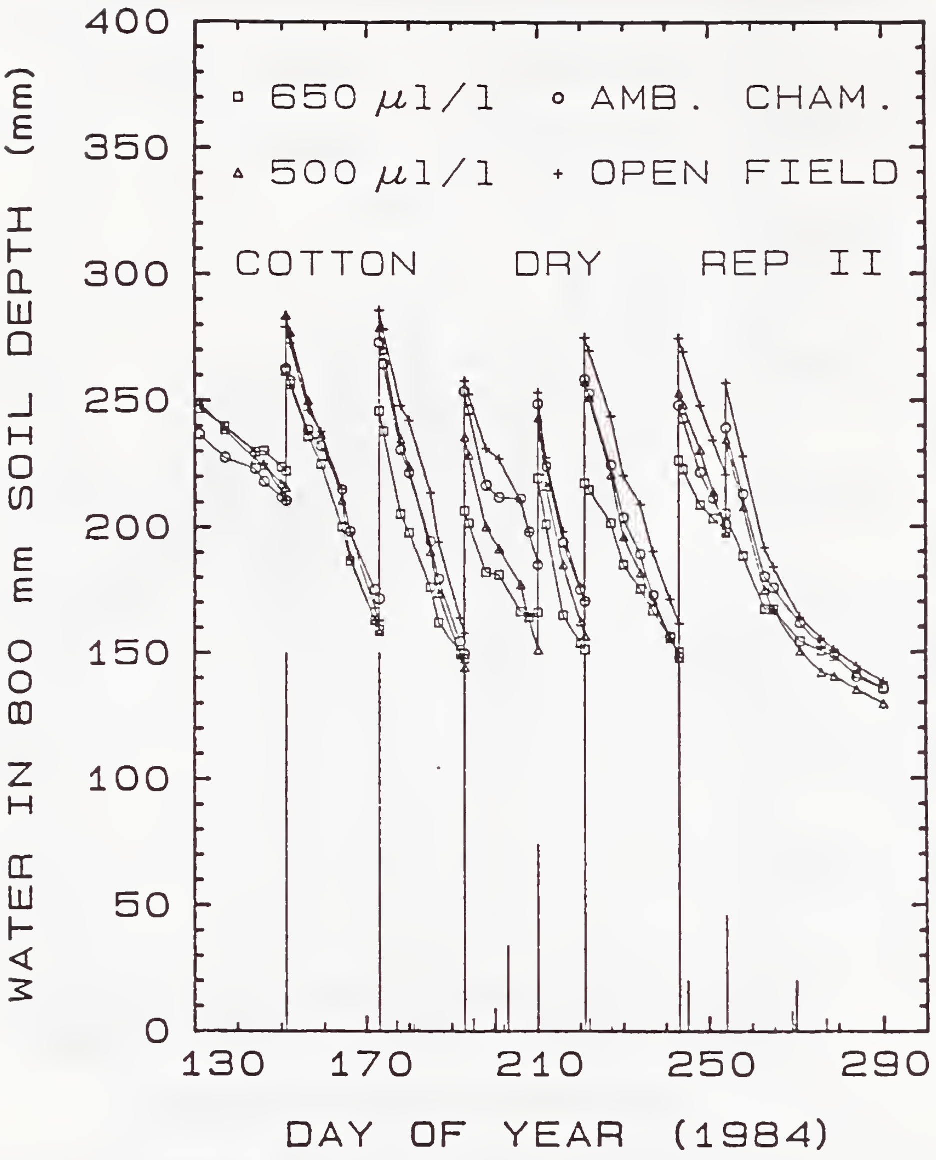

Figure 25. Total water content in the top 800 mm of soil of the Rep II - dry plots against the day of year. Also shown are the amounts of irrigation and rainfall (amounts less than 150 mm).

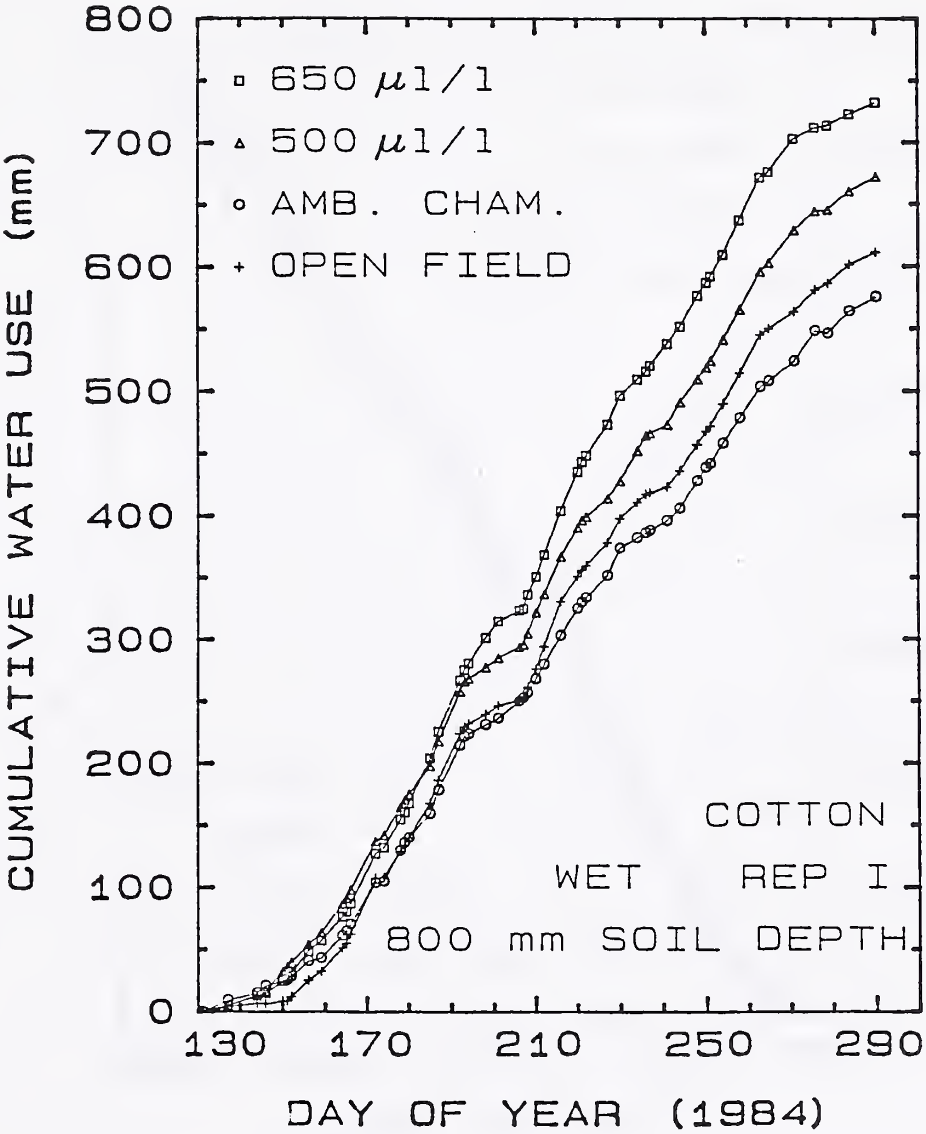

Figure 26. Cumulative water use from the top 800 mm of soil for the Rep I - wet plots.

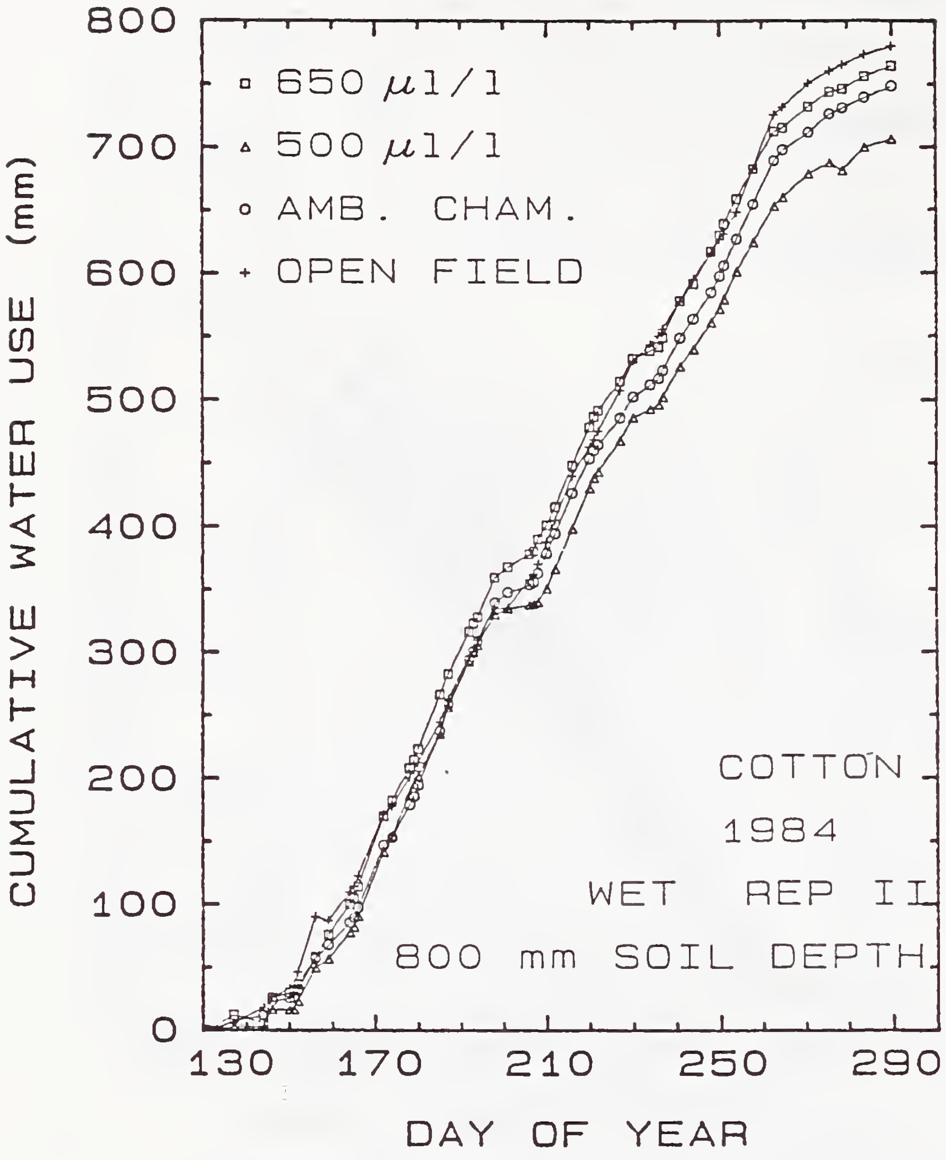

Figure 27. Cumulative water use from the top 800 mm of soil for the Rep II - wet plots.

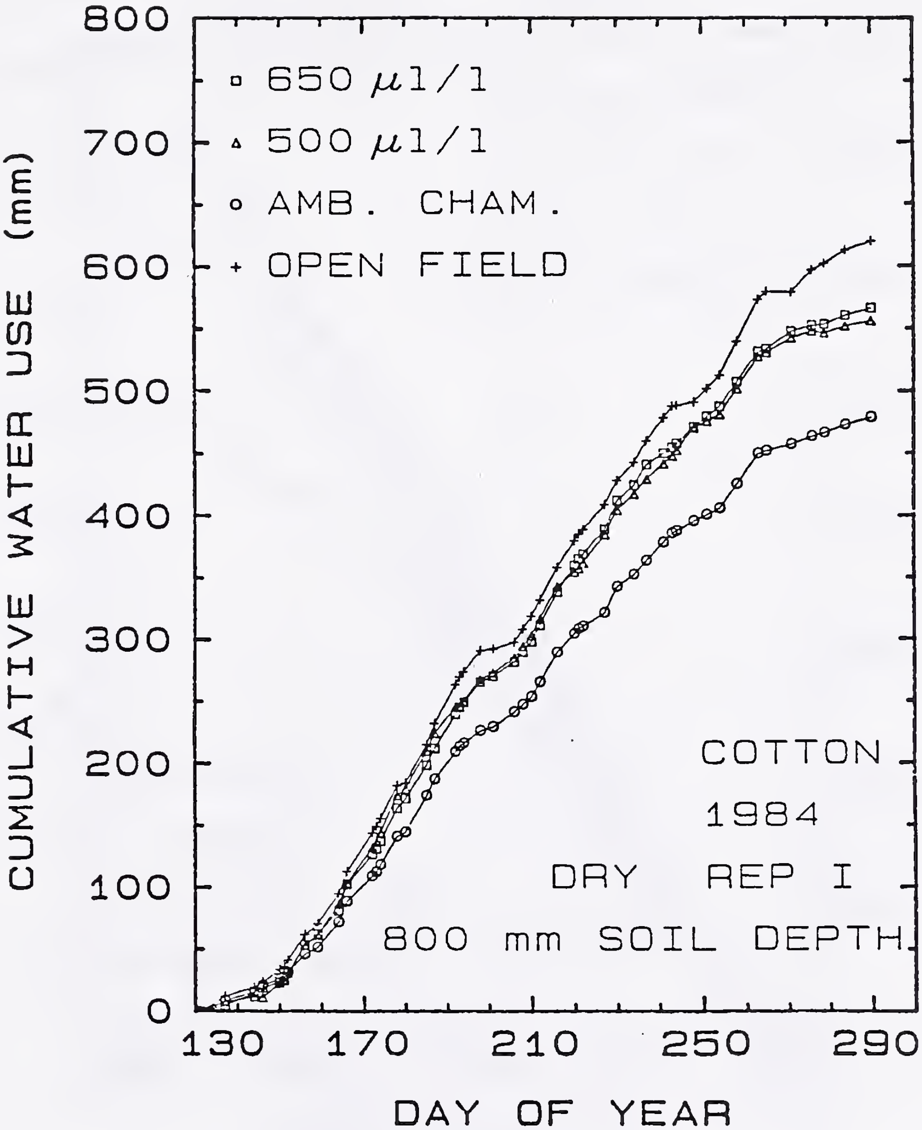

Figure 28. Cumulative water use from the top 800 mm of soil for the Rep I - dry plots.

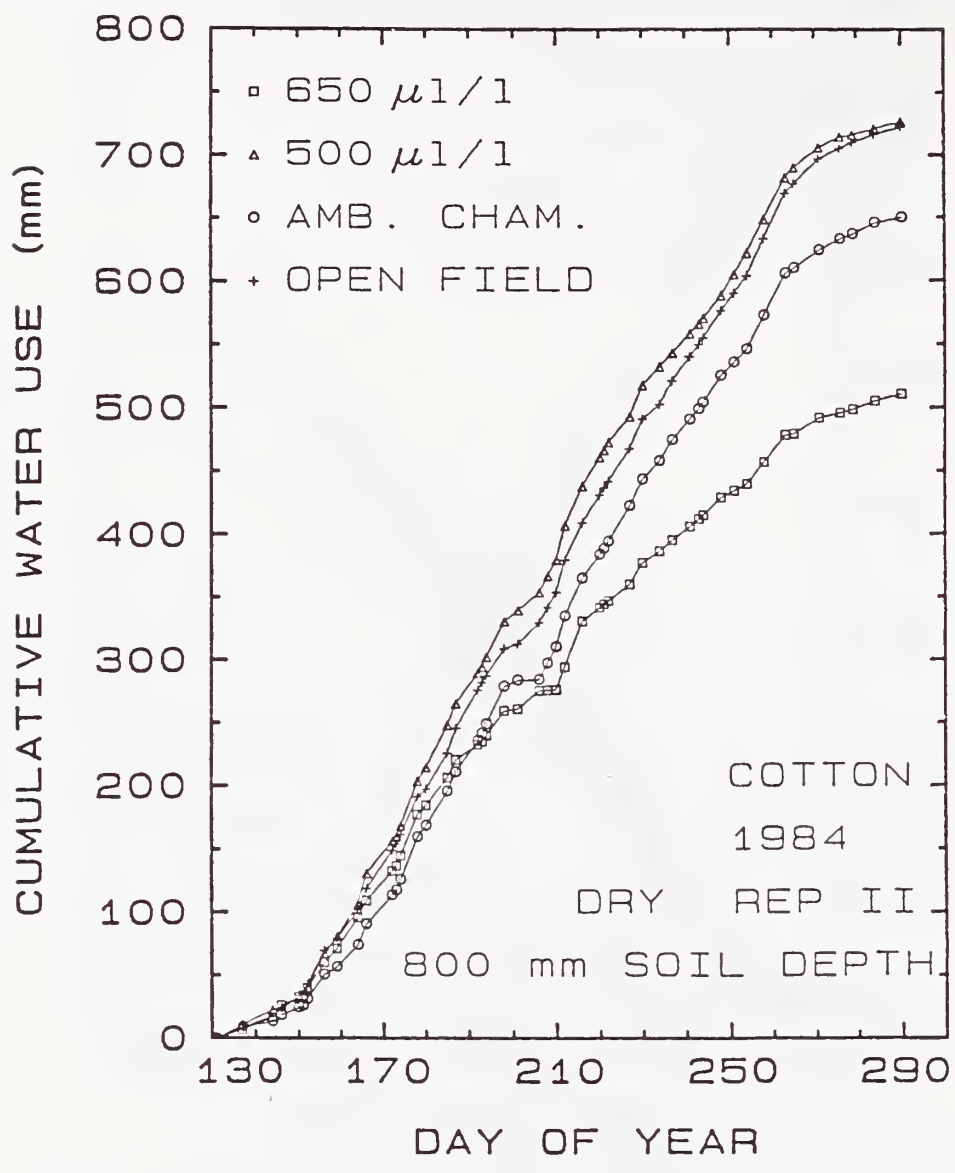

Figure 29. Cumulative water use from the top 800 mm of soil for the Rep II - dry plots.

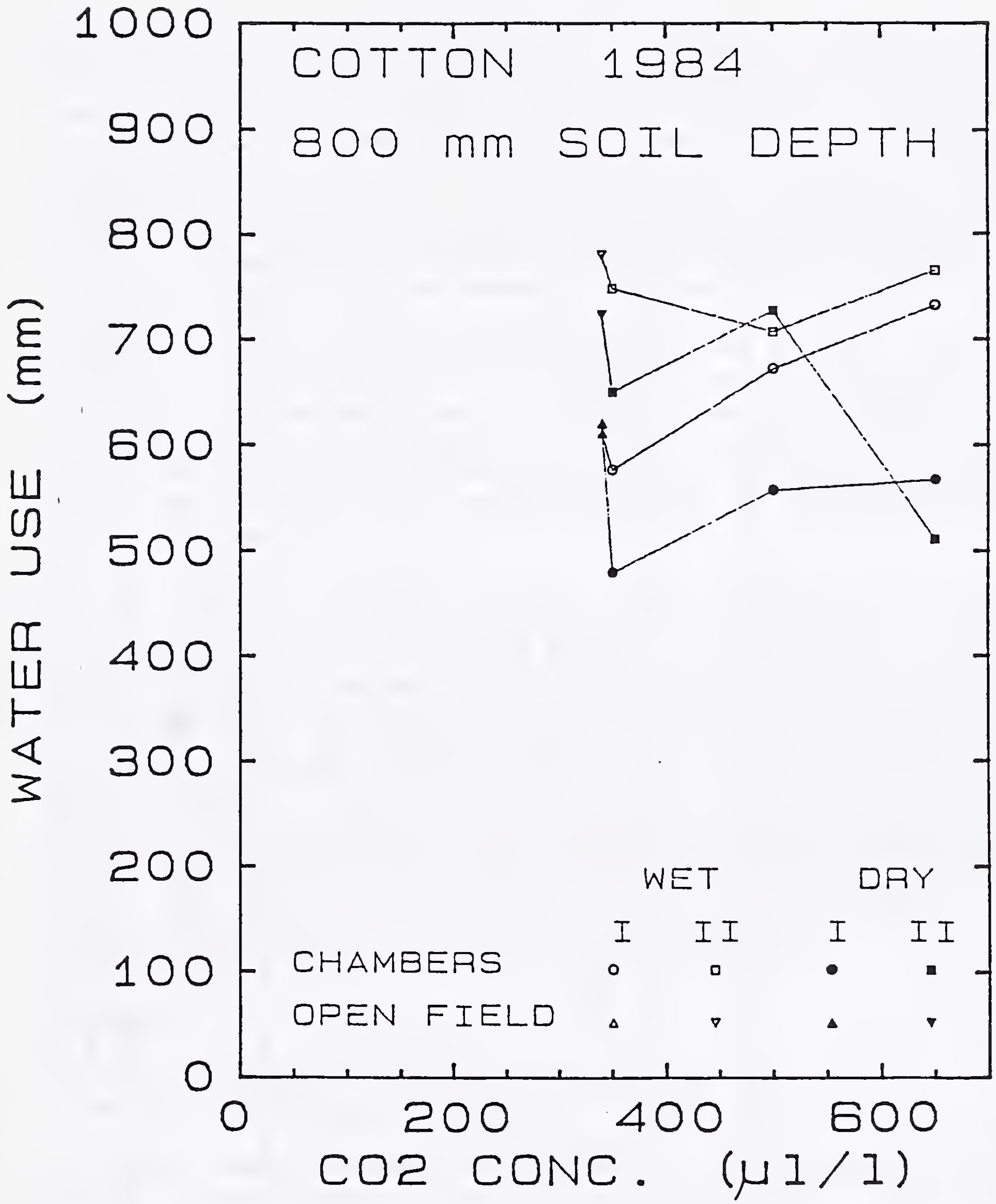

Figure 30. Total water use from the top 800 mm of soil versus CO_2 concentration for Reps I and II of the wet and dry plots.

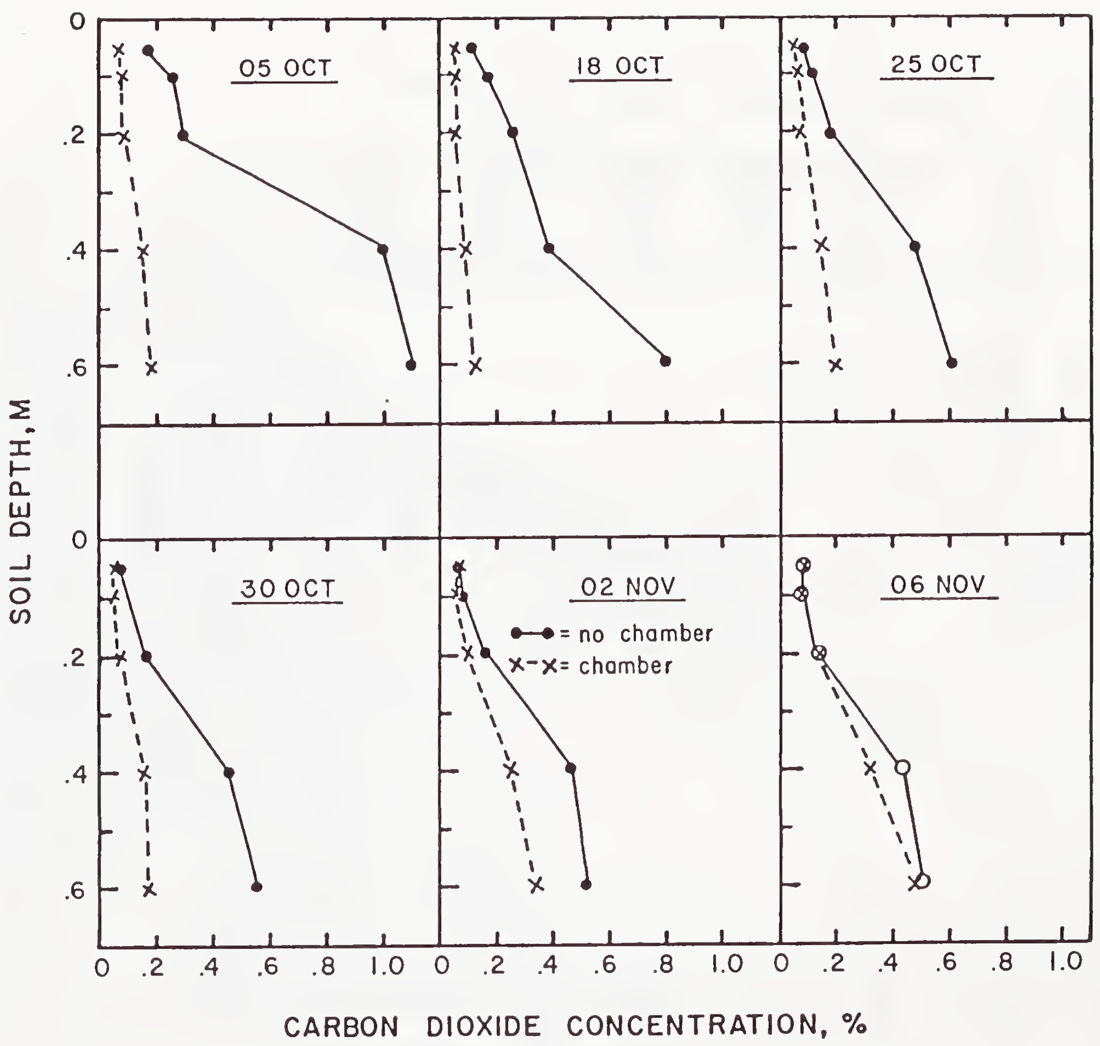

Figure 31. Soil carbon dioxide concentration at various depths inside and outside open-top chamber as a function of time. (Blower turned off in chamber after 05 Oct.)

TITLE: A SIMPLE MODEL OF BORDER IRRIGATION

NRP: 20790 CRIS WORK UNIT: 5422-20790-005

In 1984 we developed a model for describing the complete border irrigation cycle. The model was designed for blocked or unblocked sloping borders and for blocked level borders. The model can simulate irrigation on borders with variable slopes but cannot handle negative slopes or reversals in the direction of water flow. The model solves the combined equations for the conservation of mass and momentum with the acceleration terms removed. The model differs from earlier models in that the differential form of the combined Saint-Venant equations is solved. The model also simplifies the expression for the depth gradient by using an explicit value, averaged over the entire wetted border. Results for three typical irrigations (Table 1) are shown in Figs. 1-3. Comparisons of results obtained with this model to other models and field data show the model to be very stable and to give equally accurate values for advance and recession times and thus total opportunity time for infiltration over a range of conditions including level slopes. Water depths during irrigation also appear to be closely reproduced despite the use of a very simple shape factor (a linear fit between successive reaches).

For any model to be useful it must be not only accurate but also cost-efficient to use. Computationally efficient programs are required when repeated simulations are needed, such as when the effects of spatially variable hydraulic parameters are investigated. Table 2 compares the computation times for this model and the Z.I.I. model (Strelkoff and Katapodes, 1977), on an HP-1000 computer. The models were run with the same number of reaches for each simulation and yielded results of comparable accuracy. Although not a rigorous comparison of the two models, the computation times are of similar magnitude and are considerably faster than existing full dynamic models (Strelkoff and Katopodes, 1977). This model is also conceptually very simple and easy to program, requiring approximately 450 Fortran statements and 40K bytes of memory, making it adaptable to many small computing systems.

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STRELKOFF, T. and KATOPODES, N. D. 1977. Border-irrigation hydraulics with zero inertia. Proc. Am. Soc. Civ. Engr., Irrig. Drain. Div. J. 103(IR3):325-342.

PERSONNEL: D. B. Jaynes

Table 1. Parameters used in simulating the irrigations shown in Figures 1-3.

Figure	Border length (m)	Bottom slope	Manning n	Inflow rate (m^2 S^{-1})	Duration (min)	S* (cm S^{-b})	b
1	91.44	0.0011	0.089	0.00145	140	0.0332	0.444
2	91.44	0.0010	0.024	0.00328	38	0.607	0.2716
3	185.9	0.0	0.183	0.00627	53	0.059	0.511

* $I = St^b$, where I = infiltration depth, t = opportunity time, and S and b are empirical constants.

Table 2. Computation times required on an HP-1000 for simulations shown in Figures 1-3 using model developed here (Z.I.D.), and model developed by Strelkoff and Katapodes (1977, Z.I.I.).

Irrigation Shown in Figure:	Z.I.D.	Z.I.I.
	sec	
1	21.0	31.8
2	22.3	18.2
3	27.5	31.4

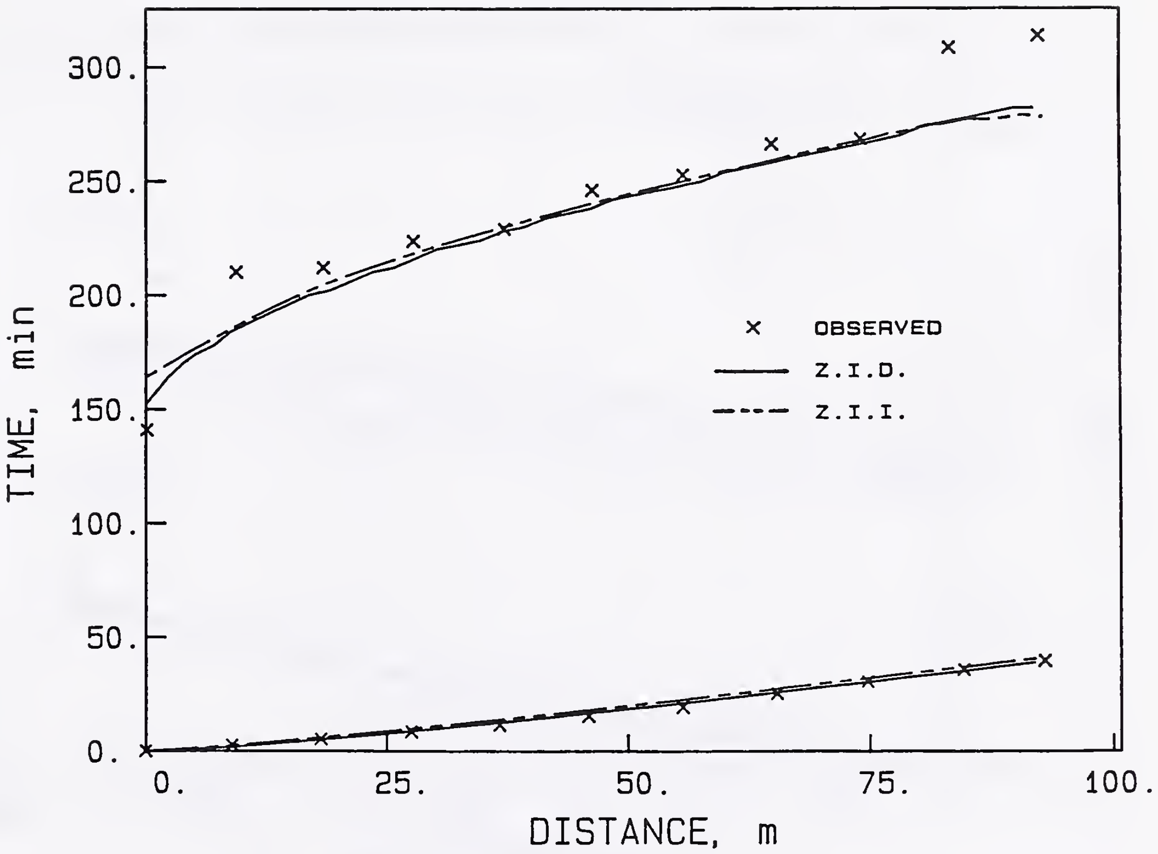

Figure 1. Calculated and observed advance and recession times for border V-5. Z.I.D. is model developed here; Z.I.I. is model developed by Strelkoff and Katapodes (1977).

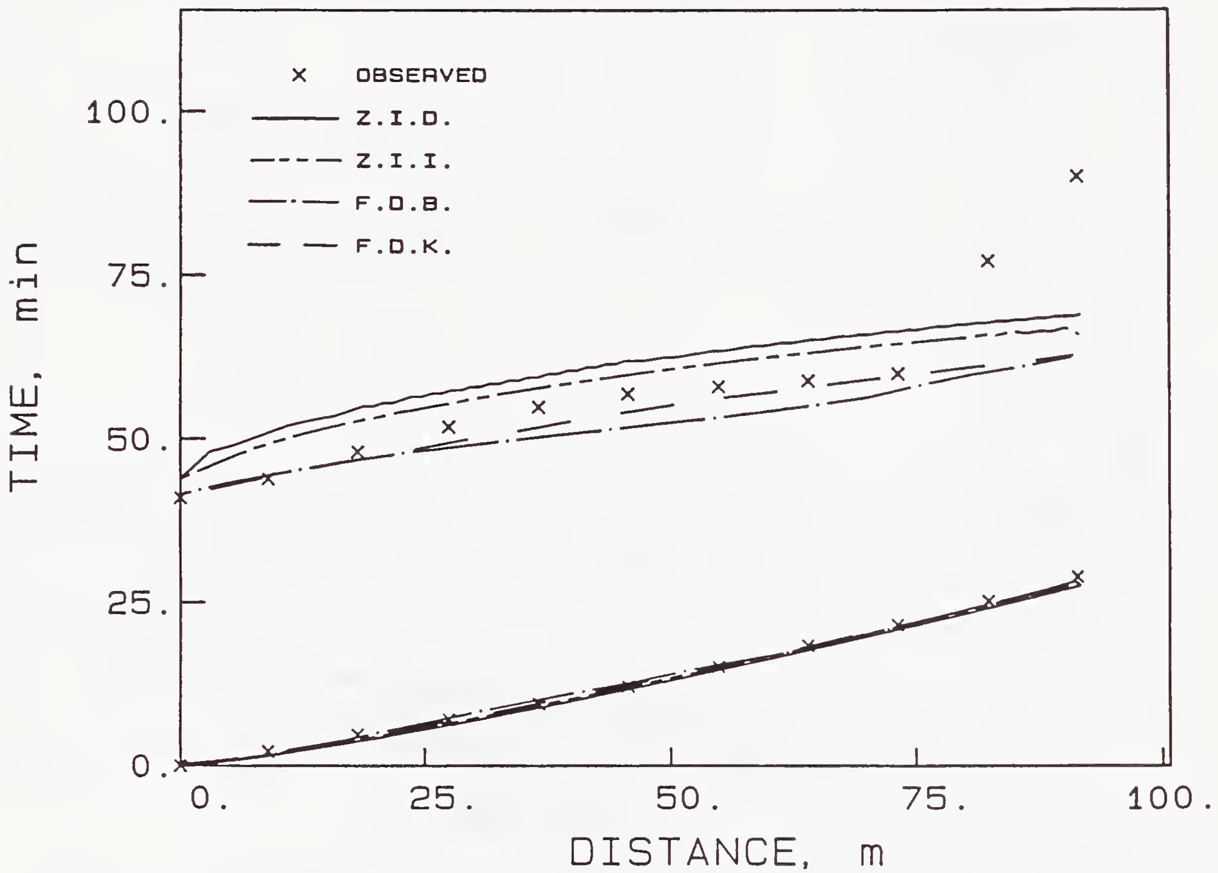

Figure 2. Calculated and observed advance and recession times for border AR-15. Z.I.D. is model developed here; Z.I.I. is model developed by Strelkoff and Katapodes (1977). F.D.B. and F.D.K. are models developed by Bassett and Fitzsimmons (1976) and Katapodes and Strelkoff (1977).

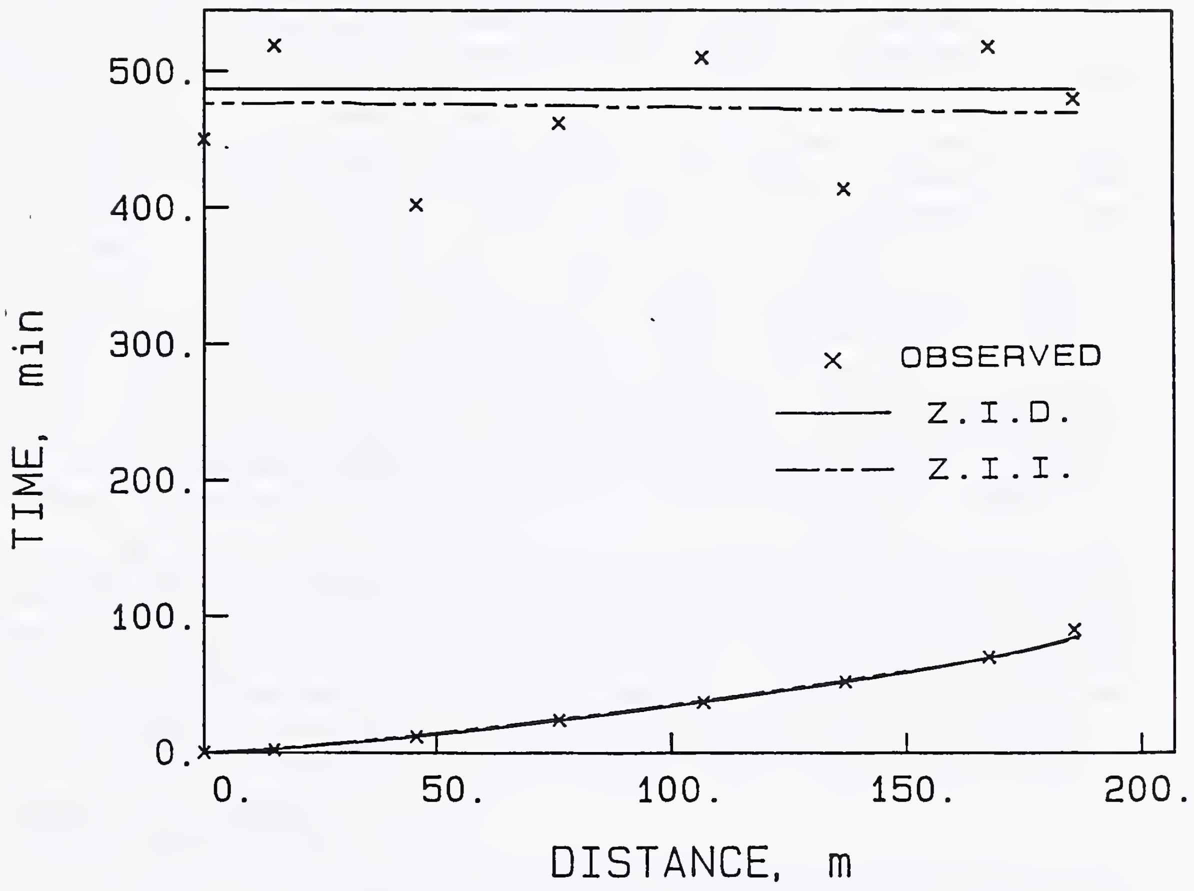

Figure 3. Calculated and observed advance and recession times for border CRC-1. Z.I.D. is model developed here; Z.I.I. is model developed by Strelkoff and Katapodes (1977).

TITLE: BROMIDE ANALYSIS IN SOIL EXTRACTS VIA AN AUTOMATED COLORIMETRIC PROCEDURE

NPS: 20790 CRIS WORK UNIT: 5510-20790-005

INTRODUCTION:

Due to its low cost, low toxicity, and small sorption potential on most geologic materials, bromide (Br^-) is often the tracer of choice in studies of soil water or ground water flow. Given the large number of samples typically generated in such studies, a rapid, reliable technique for Br^- quantitation in environmental water samples is needed. A variety of methods have been used for Br^- analysis, including ion-selective electrode (Abdalla and Lear, 1975; Onken et al., 1975), high performance liquid chromatography (HPLC) (Pyen and Erdmann, 1983; Stetzenbach and Thompson, 1983; Bowman, 1984) neutron activation analysis (Dantas and Ruf, 1975), and automated colorimetric procedures (Moxon and Dixon, 1980; Pyen et al., 1980). Electrode and colorimetric methods have been less successful for Br^- analysis in soil samples as opposed to groundwater samples. This is due to the generally higher concentrations of salts and soluble organic materials in soil water extracts, which result in interferences of varying magnitude. HPLC methods have been shown to yield accurate Br^- measurements, but analysis times are typically on the order of several minutes per sample, and many laboratories do not possess the required HPLC instrumentation. Neutron activation analysis is the most accurate of the Br^- analytical methods, but few laboratories possess in-house capability for utilizing this technique.

A recent automated procedure by Marti and Arozarena (1981) offers promise for rapid analysis of Br^- in soil extracts. This procedure, based upon the reaction of hypobromous acid with with fluorescein to form the pink Eosin (Hahn, 1933; Oosting and Reijaders, 1980) is much less subject to interferences from inorganic ions common in soils than are the other colorimetric methods. Therefore, the possibility of modifying this technique for analysis of Br^- in soil extracts was investigated.

MATERIALS AND METHODS:

The principles of the analytical method are discussed in the references cited above. Following Marti and Arozarena (1981), a manifold for the Technicon Autoanalyzer II system was constructed. A schematic diagram of the manifold is presented in Fig. 1.

Initial validation experiments indicated that soluble components present in soil extracts interfered with accurate Br^- quantitation. These interferences appeared to be primarily soluble organic compounds. Therefore, a procedure utilizing activated charcoal was developed in an attempt to remove the interfering substances from solution without affecting Br^- levels.

Five agricultural soils from the western United States were chosen for validation studies. A surface sample (0-300 mm) of each soil was used

to provide a "worst case" scenario, since organic matter content generally is greatest near the soil surface. The soils were Avondale silty clay loam (fine-loamy, mixed, hyperthermic Torrifluventic Haplustoll), Mohall sandy loam (fine-loamy, mixed, hyperthermic Typic Haplargid), Haverson loam (fine-loamy, mixed (calcareous) mesic Ustic Torrifluvent), Palouse silt loam (fine-silty, mixed, mesic Typic Haploxeroll), and Glendale clay (fine-silty, mixed (calcareous) thermic Typic Torrifluvent). The first two soils are from Arizona, while the latter three are from Colorado, Washington, and New Mexico, respectively. Some characteristics of these soils are presented in Table 1.

Twenty-five gram samples of each soil (air-dry, <2 mm) were added to 50-ml polypropylene centrifuge tubes. To each sample was added 25 ml of KBr solution with a concentration 0.0, 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, or 8.0 ppm. Bromide solutions were prepared in 0.1 M KNO_3 to minimize Br^- sorption by activated charcoal (Kamiuria _et al._, 1983). A soil-less blank was also prepared. Each sample and blank was prepared in triplicate. The tubes were equilibrated on a reciprocating shaker for 10 min., then centrifuged to yield a clear supernatent solution. Supernatents were then filtered through Whatman #541 filter paper.

An aliquot (5 ml) of each supernatent was added to a clean centrifuge tube, followed by the addition of 0.1 g of activated cahrcoal. The mixture was shaken by hand, then filtered through a 0.45 μm filter to remove the charcoal. The filtered extracts were then analyzed following the procedure of Marti and Arozarena (1981) using the manifold shown in Fig. 1. Bromide concentrations were calculated from a standard curve prepared using standards (in 0.1 M KNO_3) which had also received the charcoal treatment.

RESULTS AND DISCUSSION:

The mean Br^- recovery data for the five soils are listed in Table 2 and presented graphically in Fig. 2. Although the accuracy of the method was greatly improved over the procedure without the activated charcoal treatment, significant interferences still occurred. In three of the soils (Avondale, Mohall, and Glendale) a positive bias was noted, while the other two soils showed negative recoveries. Primarily negative interferences were noted when no charcoal treatment was used. The trend in recoveries is more or less the opposite of the trends in soil organic carbon content and total organic carbon of soil extracts (Table 1), which supports the assumption that soluble organics caused much of the negative interference problem.

The impression from the data is that both positively and negatively interfering substances are present in the extracts. Charcoal addition, depending upon the soil, removes some or all of the negatively interfering compounds. Some interferences, which aren't removed by the charcoal (or are possibly added by the charcoal itself), absorb light at the analytical wavelength of 520 nm and cause positive interference. In the high organic carbon soils, perhaps insufficient charcoal was added, and the negative interferences predominated.

For in-house purposes, the method as it stands may be adequate. With both the Arizona soils, accuracy at the 1.0 ppm Br^- level is within 10%. This level of accuracy is superior to most methods of Br^- analysis.

SUMMARY:

An automated colorimetric procedure was modified for analysis of Br^- in soil extracts. The method yields accurate Br^- quantitation at the ppm level in Arizona soils of immediate interest to our current research program. The technique was less accurate for other soils examined. The method's charcoal pretreatment step approximately doubles the time required for sample analysis compared to the autoanalyzer procedure without the pretreatment.

PERSONNEL:

R. S. Bowman, M. A. Milczarek, R. C. Rice, G. C. Auer

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Table 1. Organic carbon contents (%), total organic carbon concentration (mg/L) of a 1:1 soil:water extract, and cation exchange capacities (mole Na+/kg) of soils used in Br^- validation studies.

Soil	Organic C	TOC	CEC
Avondale	1.9	37	0.215
Mohall	0.7	31	0.175
Haverson	1.2	180	0.157
Palouse	2.9	150	0.143
Glendale	0.8	69	0.170

Table 2. Mean bromide recoveries for the five soils.

Br^- added	Recovery (%)				
(ppm)	Avondale	Mohall	Haverson	Palouse	Glendale
0.1	244	234	<0	<0	801
0.2	132	142	<0	<0	437
0.5	106	120	37	<0	234
1.0	104	108	69	46	167
2.0	103	105	82	74	137
5.0	107	105	98	92	120
8.0	104	106	100	96	108

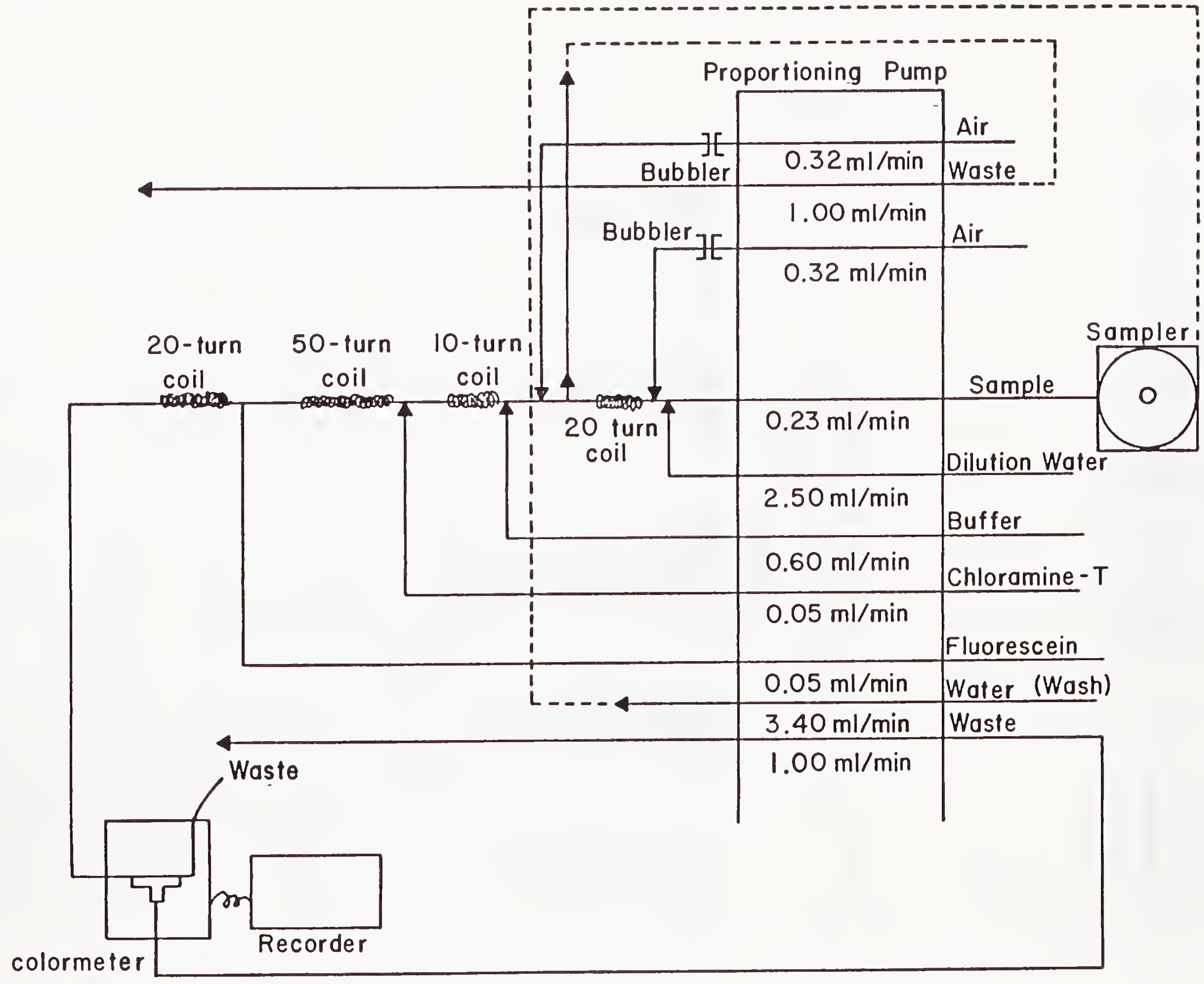

Figure 1. Bromide manifold for Technicon Autoanalyzer II system. Shown with a 1:10 dilution loop installed. For the analyses described in this report, the dilution loop and dilution water line were omitted, and a 2.50 mL/min line was used for the sample.

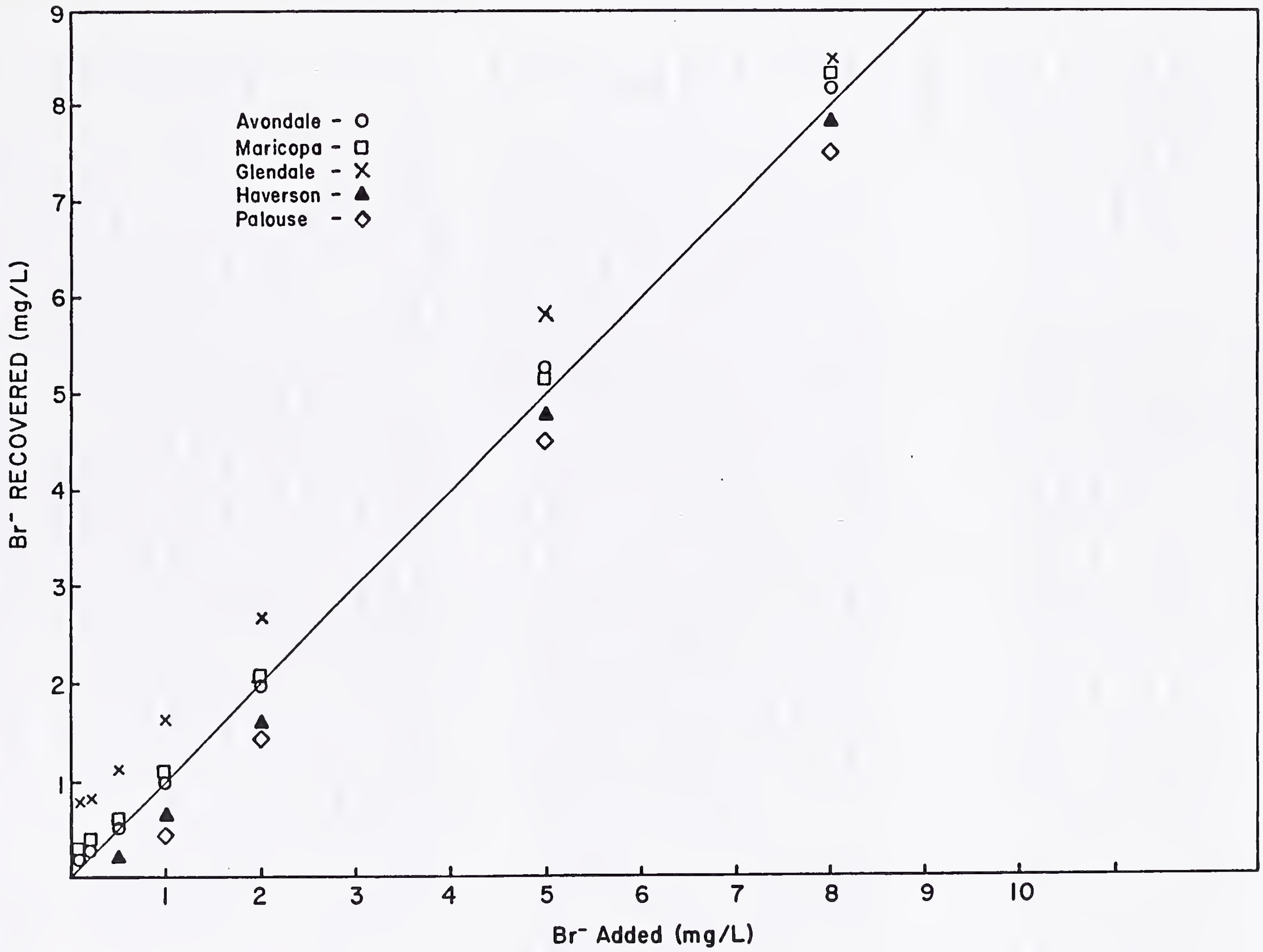

Figure 2. Bromide recoveries at different initial concentrations for the five soils.

TITLE: LONG-TERM EFFECT OF IRRIGATION ON RECHARGE AND QUALITY OF GROUNDWATER

NRP: 20790 CRIS WORK UNIT: 5510-20790-005

SPATIAL VARIABILITY OF DEEP PERCOLATION RATES:

Recharge due to deep percolation from irrigated fields must be better quantified to predict the effect of irrigation on groundwater quality. Deep percolation is frequently determined by water balance techniques with measurement errors accumulating in the deep percolation component. The object of this project is to measure point deep percolation rates over a field, using tracer techniques to determine the spatial distribution and an accurate estimate of average deep percolation. The measured deep percolation rate was compared with the rate calculated from a water balance.

PROCEDURE:

Deep percolation of excess irrigation water was measured on a bare soil. Deep percolation rates were determined from the movement of bromide added to the soil as a tracer. The field was divided into fourteen plots, 24.4 m X 18.3 m. Each plot was again divided into quarters with one quarter of each plot randomly selected for sampling. Neutron access tubes were installed in the selected subplots to depths that varied from 2.0 to 2.7 m. Potassium bromide (KBr) was uniformly sprayed onto each sampling plot. A 10 cm irrigation was applied to the plot in December, immediately after the bromide was added. Seven additional 5 cm irrigations were applied during the next 159 days. Using a 2.1 cm diameter King tube, soil samples were taken in 30 cm increments to 270 cm. Two sets of samples were obtained from each plot. The first samples were taken 5 days after the first irrigation. Additional samples were taken before subsequent irrigations. Bromide concentrations were determined from a 1:1 soil water extract.

An additional experiment was conducted to determine the effect of sample size on bromide recovery. Potassium bromide was applied to one 9 X 12 m plot followed by a 10 cm irrigation. Twenty sub-plots were sampled on a 1.8 X 2.4 m grid 6 days after the water application. Samples were taken at 15 cm intervals to a depth of 105 cm. A 10.25 cm diameter sample tube was pushed into the soil using a hydraulic sampling device mounted on a tractor. While the sample was still in the tube, a 2.18 cm diameter tube was centered inside the larger tube and a small concentric sample was obtained. The samples were then analysed for bromide. Statistical comparisons were made between the large and small sample size pairs at the different area and depth locations. The comparisons were for Br^- concentration, water content, and mass recovery (mg Br^-/kg soil). For each characteristic, the variances and means of the two populations were compared. In addition, the slope at the regression line was tested to see if it was significantly different from 1.0.

Meteorological data was routinely collected to estimate soil evaporation. Parameters measured were solar, net, and reflected radiation, air temperature, relative humidity, soil heat flux, and windspeed.

RESULTS:

Spatial Variability Study: The depth of maximum bromide concentration was determined for each of the 28 sampling sites and sampling times. The mean, mode, and median for a given sample time were essentially equal. Thus, these values appeared to be normally distributed. Assuming the values are normally distributed, the arithmetic mean can be used to estimate the average tracer velocity. The mean depth of maximum Br^- concentration for each sampling time was determined. The first 10 cm irrigation displaced the tracer peak downward about 50 cm. If the tracer had moved as piston flow, the peak would be at about 40 cm after the initial infiltration. No upward movement of the tracer was observed, indicating that the tracer was always below the zero flux plane or the zone of upward movement due to evaporation. The rate of downward movement of the tracer peak was constant at 1.03 cm/day from 50 to 120 cm and then increased to 1.61 cm/day below 120 cm. Using the tracer velocities and the average water content, the Darcy velocity was .30 and .37 cm/day for the upper and lower zones, respectively. The deep percolation calculated from a water balance was 8.1 cm after 126 days for an average of 0.065 cm/day. The average Darcy velocity from tracer movement was 5 times faster than the water balance velocity. The large deviation from piston flow indicates that the tracer, and consequently the bulk of the water, was moving in preferential paths. Anion exclusion could account for only a small portion of the difference. A transfer function model was used to predict the movement of solute to greater depths from data collected near the surface. The predicted and measured depth-concentration relationships are shown in Figure 1 for the different sample times using day 5 as the calibration data. The measured values are the arithmetic mean of 28 samples for each depth. Two different values were used for the infiltration term: (1) deep percolation as estimated from the water balance, and (2) infiltration estimated from tracer velocity and water content. The predicted curve using the tracer velocity as input for infiltration showed the solute peak at the approximate depth of the measured curve, but the maximum concentration was considerabaly smaller as the solute peak moved downward. When the deep percolation data from the water balance was used for infiltration, the predicted curve did not agree with the measured curve. This again suggests that water is moving in preferential paths and bypassing a portion of the profile.

Sample Size Study: Comparisons of the Br^- concentration and water contents for the large and small sample size are shown in Figures 2 and 3 respectively. The variances of the two populations were not significantly different in each of the three comparisons (Br^- concentration, water content, and Br^- recovery). The mean of the Br^- concentration of the large sample averaged 3.08 mg/ℓ more than the small sample which was significant at < 0.01 level. The mean of the water contents were not significantly different. The mean of the Br^- recovery for the large samples averaged 2.13 mg/kg more than the small samples and was significant at < 0.05 level. The slope of the regression line was not significantly different from 1.0 for both the Br^- concentration and recovery. The regression comparing water contents of the two sample sizes had a

slope of 0.902 which was significantly different from 1.0 at the 0.001 level.

Although there was a significant bias toward the larger sample for both Br^- concentration and Br^- recovery, the position of the depth of the maximum Br^- concentration was the same for all 20 plots. The shapes of the depth-concentration curves were essentially the same for all 20 plots.

SUMMARY AND CONCLUSIONS:

Deep percolation of excess irrigation water was measured on a 0.62-ha bare soil field. Deep percolation rates were determined from bromide added to the soil as a tracer. Core samples were taken at a depth to 270 cm within 14 subplots after each irrigation. The depth of the maximum bromide concentration was uniformly distributed over the field. The average deep percolation rate was determined from the arithmetic mean of the tracer velocities and water content. The deep percolation rate calculated from the tracer velocities was about 5 times greater than determined from a water balance. The discrepancy between the tracer and water balance rates indicates that much of the water is moving in preferential paths. The water balance may underestimate the travel times of solutes and pollutants to the groundwater.

A comparison of Br^- concentrations between 10.2 cm and 2.2 cm sample diameters showed no significant differences between the variances. The slope of the regression line relating the Br^- concentrations of the large and small samples was not significantly different from 1.0.

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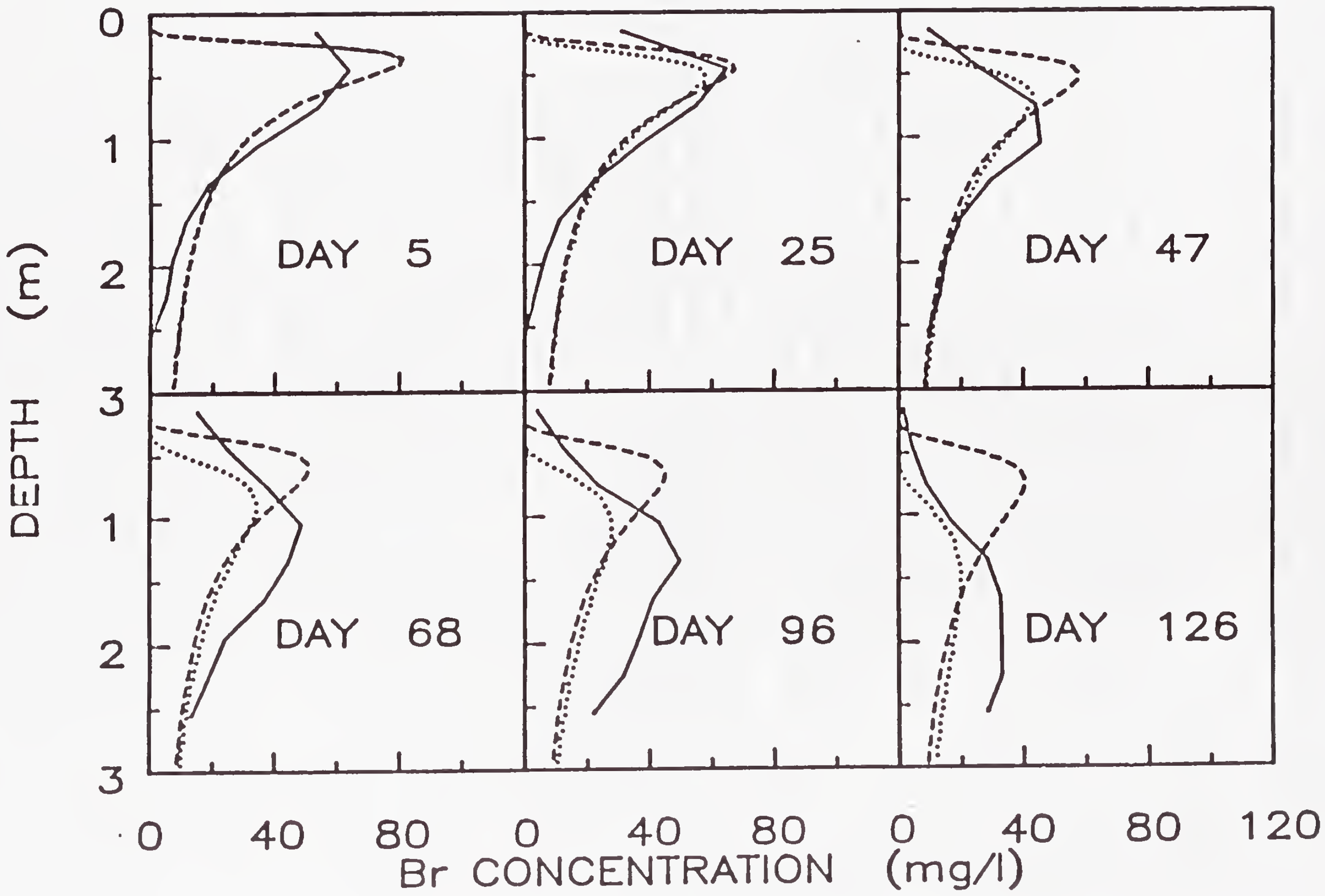

Fig. 1. Predicted and measured concentration versus depth profiles for various times after initial application. Predictions are for infiltration amounts from water balance (dashed line) and tracer (dots). Solid line is measured curve.

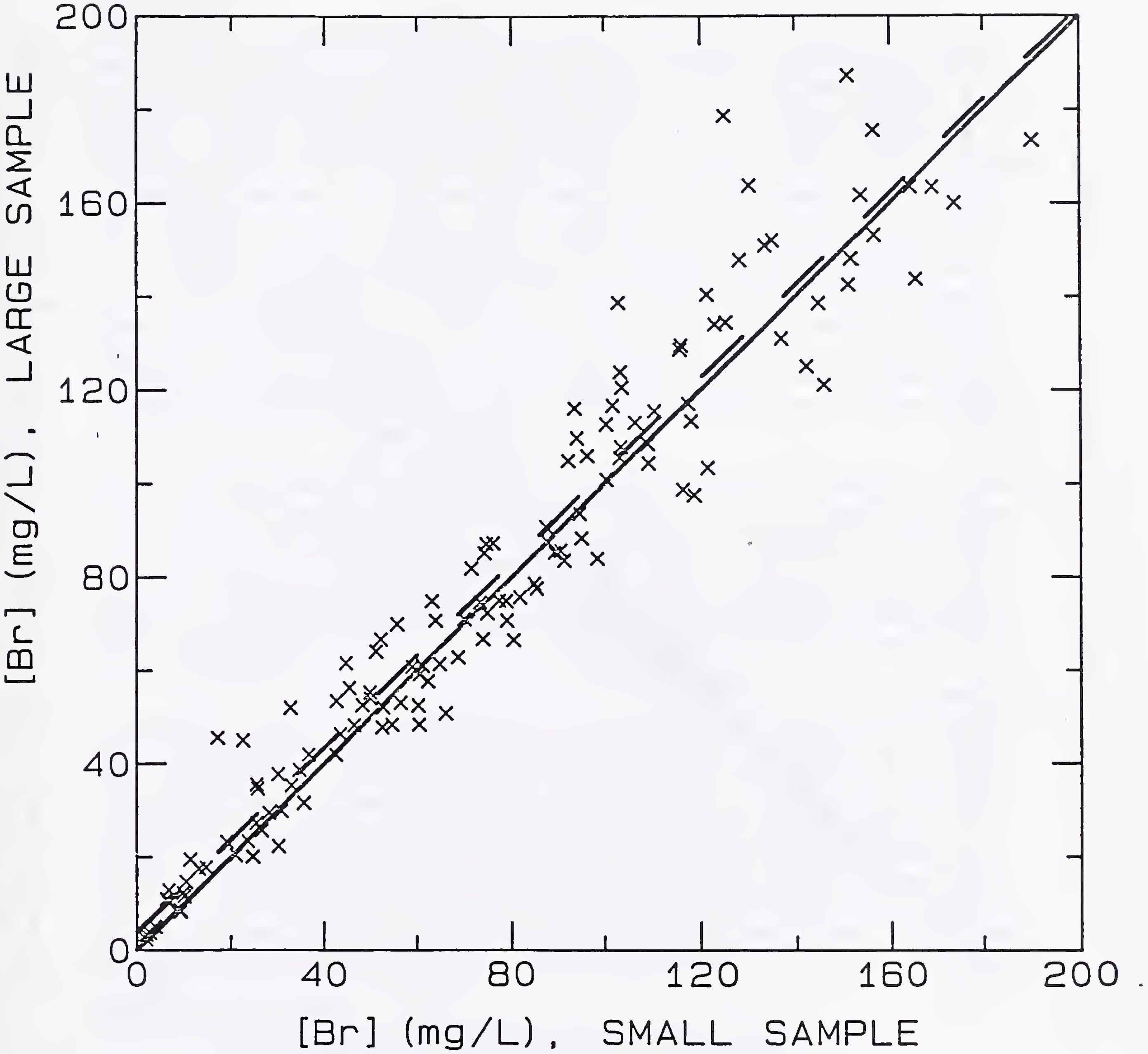

Figure 2. Br^- concentration for small and large samples. Solid line is the 1:1 line and dashed line is the regression line.

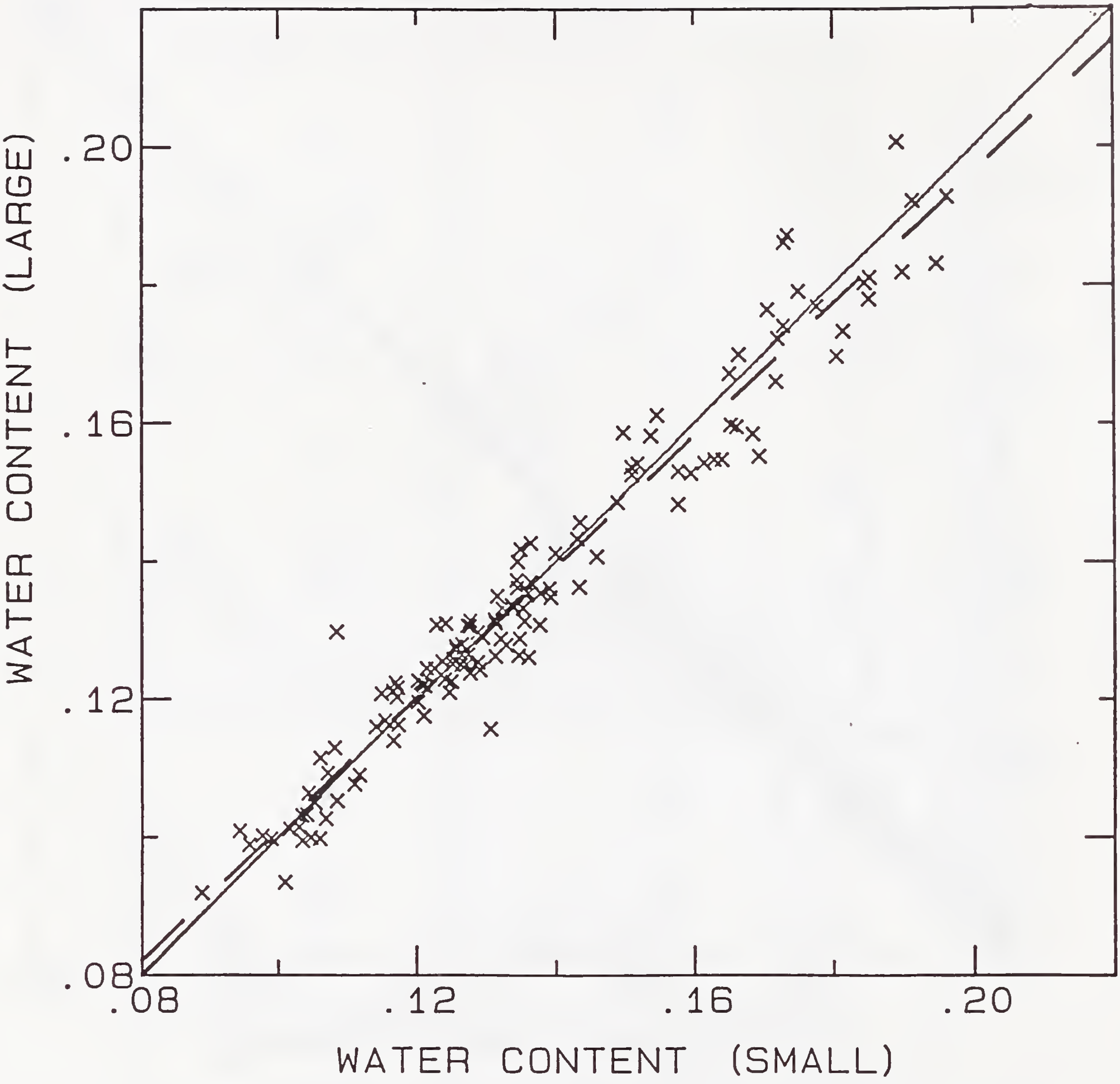

Figure 3. Water content for small and large samples. Solid line is the 1:1 line and dashed line is the regression line.

TITLE: MEASUREMENT OF SOLUTE VELOCITIES BELOW FLOOD-IRRIGATED FIELDS

NRP: 20790 CRIS WORK UNIT: 5510-20790-005

INTRODUCTION:

The ability to measure and predict downward rates of water and solute movement below agricultural fields is critical for evaluating effects of surface management practices on groundwater recharge and recharge water quality. Under irrigated conditions, this reduces to the problem of delineating effects of soil type, soil structure, irrigation method, and irrigation frequency on subsurface water redistribution. Much of the experimental work done under field conditions has concerned itself with water movement under steady state and/or unsaturated flow conditions. For instance, Biggar and Nielsen (1976) examined solute velocity and dispersion coefficient distributions under continuous ponding conditions. Van de Pol et al. (1977) considered downward rates of chloride and tritiated water movement under steady-state, trickle-irrigated conditions. Jury et al. (1982) followed the leaching of a bromide tracer, initially applied to the soil via a sprinkler system, as it moved downward in response to natural rainfall.

In the western United States and in many other areas of the world, agricultural water application is via intermittant flood irrigation. Under this system, the soil surface is ponded for a relatively brief period (on the order of hours), followed by a period of redistribution and drying (typically on the order of several days to several weeks). The characteristics of subsurface water movement in response to different flood irrigation regimes have received relatively little attention from soil scientists.

The purpose of this study was to evaluate subsurface water movement under intermittant flood irrigation. A series of conservative tracers were utilized in a controlled field environment for this purpose. The following specific questions were asked: i) what is the relationship between tracer-measured water velocities and the average pore water velocity calculated from a water balance? ii) how does the downward velocity of water under a uniform irrigation regime change over time? iii) what effects do changes in irrigation frequency have upon measured water velocities? This report concerns itself primarily with the first of these three questions.

MATERIALS AND METHODS:

Field Plot Design:

The experiments were performed in a bare field plot established on Avondale silty clay loam (fine loamy, mixed, hyperthermic Torrifluventic Haplustoll) at the U. S. Water Conservation Laboratory in Phoenix, AZ, USA. The soil shows significant variability with depth, grading from the surface silty clay loam to a clay loam which extends from the 0.7 m to 1.7 m depth, and to layers of loam, silt loam, and sandy loam between

1.7 m and 3.0 m. Below 3.0 m, large rocks and boulders are present within a sand matrix.

The 37-m^2 field plot was isolated from the surrounding soil by a 0.4-m wide sheet metal border set 0.2 m into the ground. Similar borders were used to define a 13-m^2 area in the center which was further divided into four quadrants or subplots of 3.2-m^2 area. All measurements were made within the four subplots although the entire 37-m^2 area received the same treatment in terms of water applications and tracer additions. The 23-m^2 area surrounding the subplots served as a buffer zone between the measurement area and the surrounding soil.

Each of the four subplots received a neutron probe access tube, installed to a depth of 3 m, and seven ceramic soil solution samplers placed at depths of 0.3, 0.6, 1.0, 1.4, 1.8, 2.4, and 3.0 m. Precautions were taken to minimize "short circuiting" of irrigation water down the access tubes and sampler connecting tubing. A 0.2-m X 0.2-m aluminum plate was cut out in the center to slide over each access tube. The plate was sealed to the tube at a depth of 0.15 m below the soil surface, to prevent a direct water path down the tube sides during flood irrigations. The connecting tubing from the suction samplers was vertical to a depth of 0.15 m below the surface, at which point it was directed at a shallow angle to the soil surface, again minimizing any vertical flow along the tubing sides.

The plot was equipped with a water distribution system, with separate metered supply lines to each subplot and to the buffer region, in order to minimize water application differences across the plot. Either municipal water or water from a large mixing tank used for tracer solution preparation could serve as the water source.

During the experimentation, the entire plot was covered with foam insulation followed by plastic sheeting to minimize temperature fluctuations, evaporative losses, and water input via rainfall.

Experimental Procedure:

A total of 100 mm per week of irrigation water was added during the measurement period, but the amount and frequency of water application varied. After a new irrigation regime was established, neutron probe measurements determined when the water content profile oscillated within a fixed range between irrigations. At this point, one or more tracers were added with 50 mm of irrigation water at the regular irrigation schedule. The tracers used included bromide (Br^-), m-trifluoromethylbenzoic acid (m-TFMBA), o-trifluoromethylbenzoic acid (o-TFMBA), 2,6,-difluorobenzoic acid (2,6 -DFBA), and penta fluorobenzoic acid (PFBA), at initial concentrations of 200, 40, 50, 50, and 50 mg L^{-1}, respectively. The organic tracers were previously shown to move with Br^- in this soil (Bowman, 1984a).

The first irrigation regime consisted of semi-weekly 50-mm irrigations. After the stabilization of profile water contents, a dual-labelled pulse

of Br^- and m-TFMBA was added. Solution samples were collected daily during the first week following tracer addition and three times per week thereafter. A second tracer pulse, labelled with 2,6-DFBA, was added 42 days following the Br^-/m-TFMBA pulse.

The second irrigation regime, begun after the initial tracers were no longer detectable in the suction samples, consisted of a single 100-mm irrigation per week. After stabilization of profile water contents, a dual-labelled pulse of Br^- and PFBA was added, followed by pulses of 2,6-DFBA, o-TFMBA, and m-TFMBA after 7, 14, and 28 days, respectively. Extracts were collected for 100 days following m-TFMBA addition, at which point tracers were no longer detectable in the samples.

Tracer concentrations in the suction samples were measured simultaneously by a technique described earlier (Bowman, 1984b).

RESULTS AND DISCUSSION:

Figures 1a and 1b present the relative concentration of the Br^- tracer in one of the four subplots under the semi-weekly irrigation regime. Relative concentration refers to the concentration in the sample divided by the original input concentration. Figure 1a shows the relationship as a function of time. The data are representative in showing the well-defined tracer peaks which were observed with most of the samples under both irrigation treatments. In some cases, particularly under the once-weekly 100 mm irrigations, a peak was not defined at the 0.3 m or 0.6 m depth. Except in the cases of a few malfunctioning samplers, well-defined tracer maxima were observed at all depths greater than 0.6 m.

The occurrence of irrigation water additions with respect to sampling time is also shown in Fig. 1a. Even at the shallower depths, there was no apparent fluctuation in tracer concentrations resulting from the intermittent water inputs. The tracer distributions obtained resemble those seen under steady-flow water conditions.

Fig. 1b presents the same data in terms of relative pore volume, (RPV) of water leached through the profile at each depth. The RPV was calculated for each sampler i as:

$$RPV = \frac{qt}{\Theta_i} \qquad (1)$$

where q is the known Darcy flux of 100 mm wk^{-1}, t is time, and Θ_i is the total average water storage in the profile above sampler i, as determined from the neutron probe moisture measurements. The solid lines in Fig. 1b were fitted to the concentration data using an analytical solution to the one-dimensional convection-dispersion equation

$$\frac{\partial C}{\partial t} = D_s \frac{\partial^2 C}{\partial x^2} - v_s \frac{\partial C}{\partial x} \qquad (2)$$

where C is the tracer concentration, x is sampler depth, D_s is the apparent diffusion coefficient of the tracer containing water, and v_s is

the mean velocity of the tracer containing water. D_s and v_s were adjusted to yield the best fit to each set of concentration data using the least-squares optimization method of van Genuchten (1981), assuming a semi-infinite profile and uniform steady-state water input at the surface. Cassel et al. (1975) and Wierenga (1977) have found that the steady-state solution to equation (2), using mean values for Darcian flux and profile water content, gives a good approximation of solute transport data obtained under transient conditions. This approach yielded fitted values of v_s for each tracer at each sampler which agreed well with the observed peak maxima.

Probability plots (fractile diagrams) were prepared using untransformed and log-transformed velocity data for all samplers and tracers under a given irrigation regime (Figs. 2a and 2b). The plots show that the v_s data in each case is best described by a log-normal distribution, although the normal distribution also describes the semi-weekly v_s data adequately (Fig. 2a). The reasons for the stronger log-normal character of the velocities under the once-weekly regime are not known. For consistency, v_s data for both data sets was considered log-normally distributed. Under the semi-weekly 50 mm irrigations, the 72 measured values of v_s had a mean of 67 mm d^{-1}, with a 95% confidence interval of 62 to 72 mm d^{-1}. Under the once weekly regime, the mean v_s was 57 mm d^{-1}, with a 95% confidence interval of 51 to 64 mm d^{-1}. The reasons for the decrease in mean velocity with the once-weekly irrigation are not clear.

The mean moisture profiles observed under the two irrigation regimes were almost identical. For example, the mean total profile volumetric water contents from the 0-m to 3-m depth under the semi-weekly and once-weekly irrigations were 0.329 and 0.332, respectively. Using the mean profile water storage and the mean Darcy flux of 14.3 mm d^{-1} (100 mm per week), the so-called average pore-water velocity, v_o, can be calculated from the surface to each sampler depth as

$$v_o = q/\Theta_i \tag{3}$$

Values of v_o for the various sampler depths ranged from 41 to 43 mm d^{-1}, depending upon Θ_i for a given depth. The mean value of v_o is shown as a dashed line in Figs. 3a and 3b, which present the v_s data for each sampler depth under each irrigation regime.

Figures 3a and 3b indicate that measured values of v_s, with few exceptions, were considerably greater than v_o as calculated from the water balance. Except at the 1.0 m sampling depth under the once-weekly regime, v_o lay outside the 95% confidence interval for all depths below 0.3 m. At the greater depths, particularly under the semi-weekly irrigations, v_s is about double v_o. The low mean v_s at the 1.0 m depth was caused by one sampler which consistently showed very low velocities under the once-weekly regime. Omitting data from this sampler raises the mean v_s for this depth to 46 mm d^{-1}, with v_o just inside the 95% confidence interval.

In a homogenous porous medium, v_s as determined using a non-interacting tracer should equal v_o. In the few field studies which have measured

both, v_o has been found to be equal to or greater than v_s. Biggar and Nielsen (1976) found velocities of Cl^- and NO_3^- to be, on the average, within 10% of v_o calculated from the steady-state infiltration rate and water content under ponded conditions. Van de Pol et al., working under trickle-irrigated conditions, found v_o to lie within the 95% confidence interval of v_s as measured by a Cl^- tracer. Jury et al. (1982) found tracer velocities measured at the 0.3 m depth in the field to be less than the calculated v_o. The discrepancy was attributed to the use of applied water rather than average drainage, which could not be determined under their experimental conditions, for the calculations.

In contrast to the above findings, our work indicates a solute velocity at almost all depths which is consistently greater than the calculated average pore water velocity, v_o. The ratios of the mean value of v_s to v_o were 1.6 and 1.4 for the semi-weekly and once-weekly irrigation regimes, respectively. Of the 184 velocity measurements, only 39 values of v_s were less than or equal to v_o. If the true mean value of v_s were equal to v_o, most of the measured v_s values would be less than v_o under a log-normal distribution.

There are several possible reasons which could explain the differences between v_o and v_s. Since all the tracers used were anions, anion exclusion by negatively charged soil surfaces could at least partially explain the acceleration of solute versus water. To test this possibility, a separate experiment utilizing deuterated water (HDO) was performed in one of the subplots. A dual-labeled Br^-/HDO pulse was applied under the once-weekly irrigation regime. The velocities of Br^- and HDO were determined at the five sampler locations between 1.0 and 3.0 m. The Br^- peak did arrive earlier than the HDO peak at each sampler, indicating that some exclusion of Br^- and/or retardation of HDO occurred in this soil. In all cases, however, the v_s value for HDO was greater than v_o. The mean value of v_s measured with HDO was more than 60% greater than v_o. Thus, anion exclusion was ruled out and an explanation for the high v_s/v_o ratios observed.

A second possible explanation for elevated v_s values is that leakage may have occurred along the suction sampler connecting tubing during flood irrigation. While this possibility cannot be completely eliminated, the observed velocity distributions with depth make it appear unlikely. If leakage were occurring, the effects on v_s should have been greatest at the shallower depths. The mean v_s/v_o ratios was greater than one at almost all depths, however, and generally increased with increasing depth. For example, referring to Fig. 2a, the mean v_s/v_o ratio at the 2.4 m depth as 2.0, compared to a ratio of 1.4 at 1.4 m.

The most likely explanation for the observed discrepency appears to be that v_o, as calculated from the mean Darcy flux and soil water content, was not an accurate indicator of downward percolating water velocities in this experiment. Downward-moving water was not pushing stored profile water ahead of it as in piston-displacement, but was bypassing a significant portion of the stored water. Thus, solute appeared at depth more rapidly than if complete mixing had occurred.

The concept of bypass flow is not new. Others (e.g. McMahon and Thomas, 1974; van Genuchten and Wierenga, 1977; White, et al., 1984; and references cited therein) have observed this phenomenon when working with undisturbed or aggregated soils. Such soils have a wide range in pore sizes and potential flow paths for percolating water. Even under unsaturated conditions, as were present in this experiment, most of the water movement probably occurs in only a fraction of the conducting pathways.

SUMMARY AND CONCLUSIONS:

A survey of the literature, and particularly the literature associated with modeling of solute transport under real-world conditions, shows an almost universal assumption of the identity of v_o and v_s. Our work indicates that predictions of downward travel times based on v_o will underestimate true solute mobility. The use of v_o may yield predictions of impacts of management practices on ground water quality which are not as conservative as they should be.

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VAN GENUCHTEN, M. TH., and WIERENGA, P. J. 1977. Mass transfer studies in sorbing porous media. II. Experimental evaluation with tritium (^3H_2O). Soil Sci. Soc. Am. J. 41:272-278.

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WIERENGA, P. J. 1977. Solute distribution profiles computed with steady-state and transient water movement models. Soil Sci. Soc. Am. J. 41:1050-1055.

PERSONNEL:

R. S. Bowman, R. C. Rice, H. Bouwer, and G. C. Auer

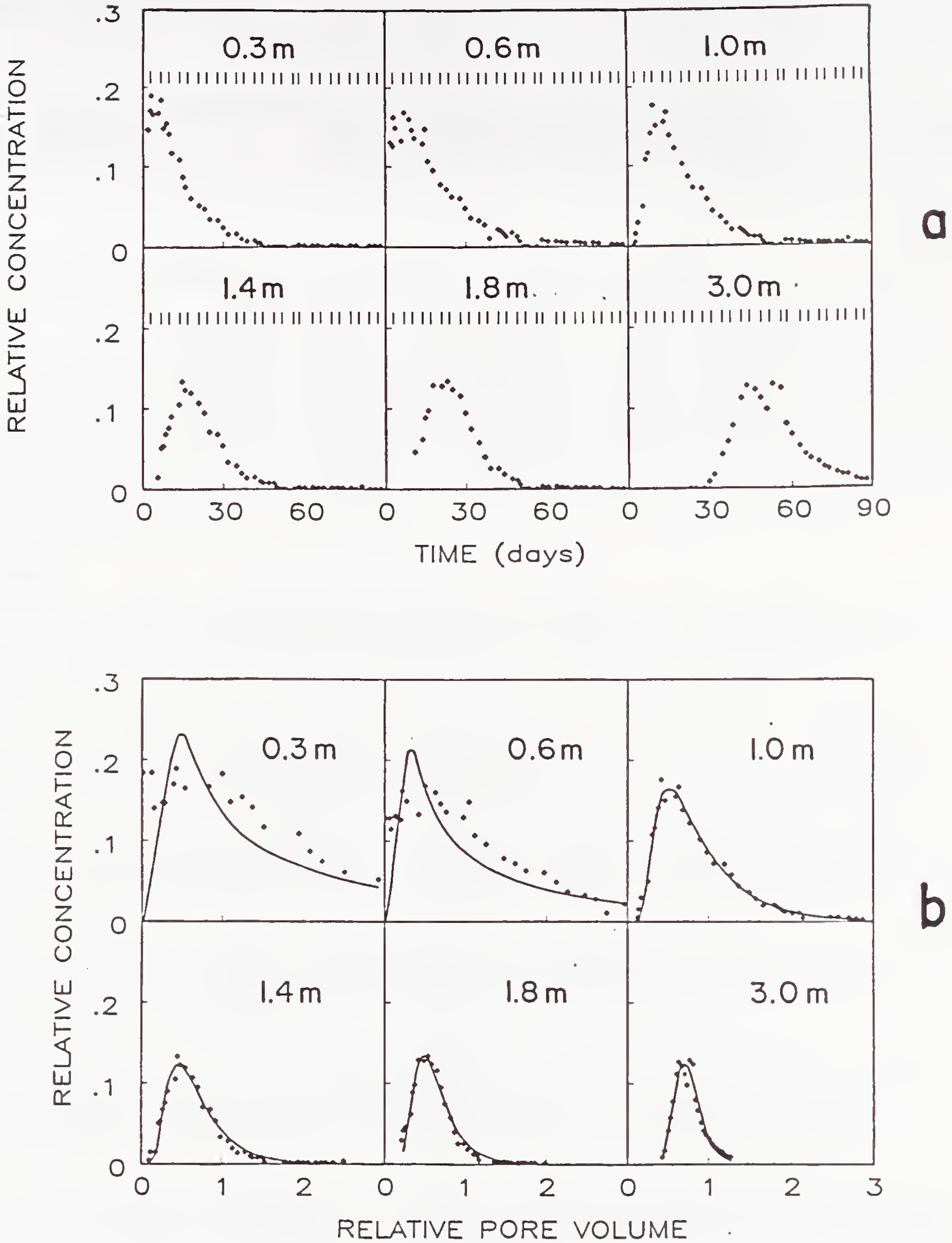

Figure 1. Breakthrough curves for Br^- at six depths in subplot 1, under the semiweekly irrigation regime. (a) Abscissa in terms of elapsed time after addition of the tracer pulse. 50-mm irrigation events are indicated by the vertical lines. (b) Abscissa in terms of pore volumes. The solid lines are curve-fitted values based on Equation (2).

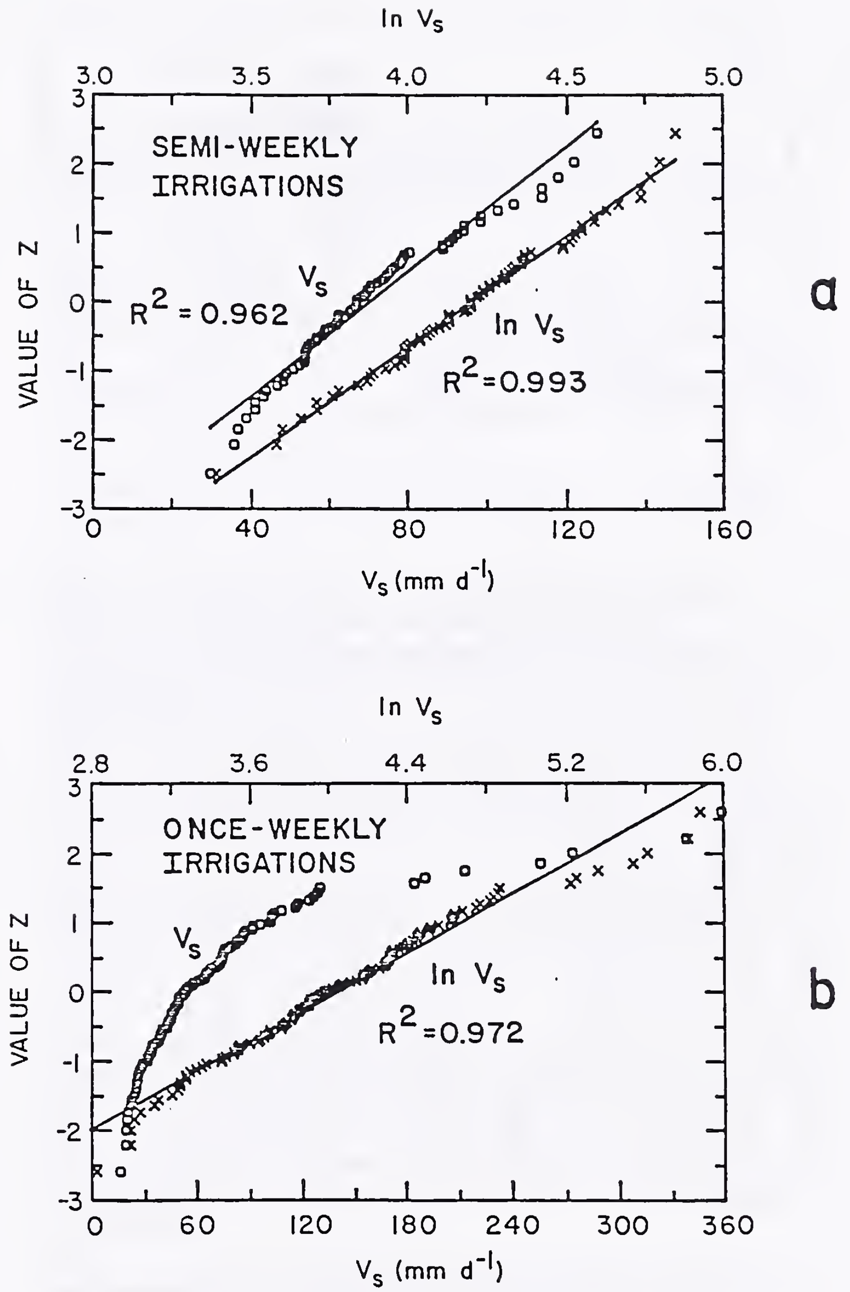

Figure 2. Fractile diagrams for v_s and ln v_s under the (a) semi-weekly, and (b) once-weekly irrigation regimes.

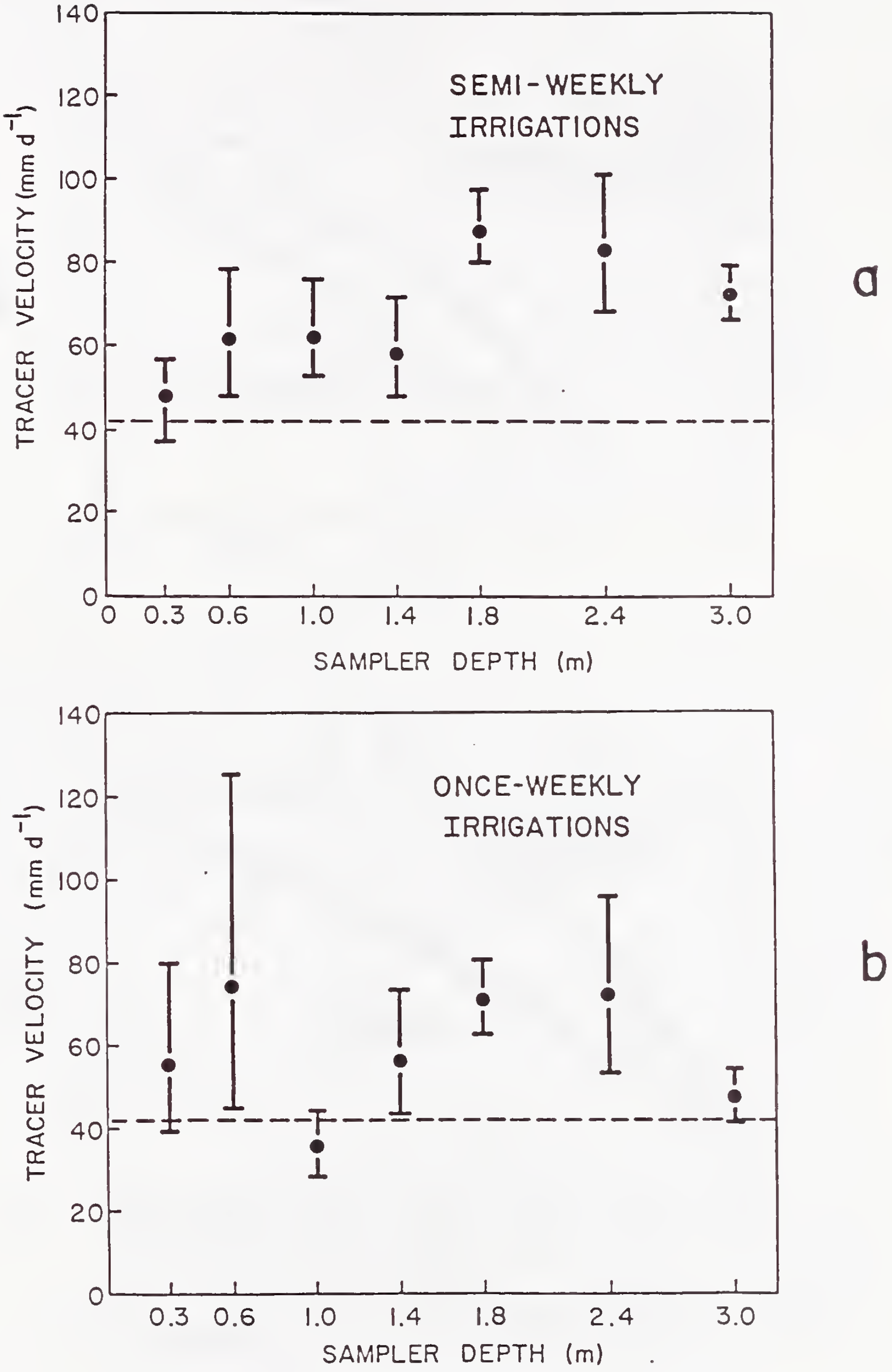

Figure 3. Mean values of v_s and 95% confidence range at each sampler depth, calculated using ln-transformed v_s values. The horizontal dashed line is the mean value of v_o as calculated from Equation (3). (a) semi-weekly, and (b) once weekly irrigation regimes.

APPENDIX

LIST OF 1984 PUBLICATIONS

AND MANUSCRIPTS PREPARED

		MS. No.
NRP 20160	GERMPLASM DEVELOPMENT AND DOMESTICATION OF CUPHEA AND OTHER NEW CROP SPECIES (Arid Zone Crop Production Research Management Unit)	
Published:	LEE, C.W., THOMPSON, A.E., JONES, W.D. and HOGAN, L. 1984. 'Centennial' Baccharis interspecific hybrid. HortScience 19:903.	1090
	THOMPSON, A.E. 1984. Cuphea--a potential new crop. HortScience 19:352-354.	971
In Press:	THOMPSON, A. E. New native crops for the arid Southwest. Econ. Bot.	1102
In Progress:	LEE, C.W., THOMPSON, A.E., JONES, W.D. and HOGAN, L. Growth characteristics of the interspecific hybrid *Baccharis sarothroides* x *B. pilularis*. Hortsci.	1091
NRP 20740	WATER AND AGRONOMIC MANAGEMENT FOR EFFICIENT COMMERCIAL GUAYULE RUBBER PRODUCTION. (Arid Zone Crop Production Research Management Unit)	
Published:	BUCKS, D.A., NAKAYAMA, F.S., and FRENCH, O.F. 1984. Water management for guayule rubber production. Trans. of ASAE. 27(6):1763-1770.	965
	EHRLER, W.L. and NAKAYAMA, F.S. 1984. Water stress status in guayule as measured by relative leaf water content. Crop Science 24:61-66.	939
	NAKAYAMA, F.S. 1984. Hydrocarbon emission and carbon balance of guayule. J. of Arid Environ. 7:353-357.	933
	NAKAYAMA, F.S. and BUCKS, D.A. 1984. Crop water stress index, soil water, and rubber yield relations for the guayule plant. Agron. J. 76:791-794.	984

		MS. No.
	NAKAYAMA, F.S. and BUCKS, D.A. 1984. Irrigation water management for optimizing guayule rubber production. Proc. Guayule Rubber Society Meeting, Washington, DC, June 17-21, 1984.	1084
In Progress:	ALLEN, S.G., TAYLOR, G.A., and MARTIN, J.M. Agronomic characterization of 'Yogo' hard red winter wheat plant height isolines.	1133
	BUCKS, D.A., NAKAYAMA, F.S., FRENCH, O.F., LEGARD, W.W. and ALEXANDER, W.L. 1984. Irrigated guayule--evapotranspiration and plant water stress. Agric. Water Management.	1094
	BUCKS, D.A., NAKAYAMA, F.S., FRENCH, O.F., LEGARD, W.W. and ALEXANDER, W.L. 1984. Irrigated guayule-production and water use relationships. Agric. Water Management.	1093
	BUCKS, D.A., NAKAYAMA, F.S., FRENCH, O.F., RASNICK, B.A. and ALEXANDER, W.L. 1984. Irrigated guayule-plant growth and production. Agric. Water Management.	1092
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